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Salinity Distribution in the Thames River: New London to Norwich, Connecticut

EMIL F. SODERBERG
ANTHONY B. BRUNO
E/M Environment and Optical Systems Division

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NAVAL UNDERWATER SYSTEMS CENTER
Newport, Rhode Island 02840

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Emil F. Soderberg
Anthony B. Bruno

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W. L. Clearwaters

W. L. Clearwaters
Associate Director, Sensors
Naval Underwater Systems Center

A

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Shallow Water Environmental Factors						

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SALINITY DISTRIBUTION IN THE THAMES RIVER: NEW LONDON TO NORWICH, CONNECTICUT

INTRODUCTION

In the course of some laboratory measurements, the need arose for information on the values of electrical conductivity of the waters of the Thames River, Connecticut. It was found that very little published data was available on the characteristics of this river. It was known that the Thames River estuary was generally saline all the way up to Norwich, that a certain volume of freshwater discharge entered the estuary from the tributaries, and that the conductivity values should therefore range from the low values associated with the fresh waters up to that of sea water. It was not known how the two bodies of water, fresh and salt, interacted in the estuary. Therefore, in April 1967, preliminary measurements of the vertical profiles of electrical conductivity and temperature versus depth were made along the length of the Thames River,[1] and in July 1968 a 12-month program of measurements was initiated to determine the variation of the fresh/salt water structure of the river throughout the year. The results of these measurements are the subject of this report.

Apparently the fresh/salt water structure of the Thames River had not been previously studied to any significant extent. Some measurements of electrical conductivity versus depth had been made in 1959 at the south pier of the New London Laboratory.[2] A very detailed survey was made of the thermal structure of the portion of the Thames River in the immediate vicinity of the Montville electric power plant in the fall of 1968.[3] Other types of measurements that have been made in the river have been based mainly on surface-water and bottom-water samples. The various measurements have been made quite independently of each other, and the number of different measurement locations has been very limited. A recent paper on water pollution cites some examples of the different kinds of measurements that have been made in the Thames River: radioactivity analysis of surface waters and bottom sediment, analysis of surface waters for pollution (both of these by the Connecticut State Department of Health), and analysis of the chemical compostion of surface and bottom waters along the river (by the United States Geological Survey, USGS).[4] The extensive work by the USGS on the inland water resources of eastern Connecticut affords a valuable and necessary adjunct to the studies of the Thames River estuary itself.[5-8] Currently there is in progress a measurement program, coordinated by the Marine Technology Society's New England Section, involving personnel of local

laboratories, industries, schools, and universities in a volunteer cooperative effort to gather long-term data on the temperature, conductivity, dissolved oxygen, pH, and chemical composition of the Thames River waters that should contribute significantly to the understanding and characterization of this estuary.[9]

The efforts described in this report were specifically directed toward determining the fresh/salt water structure of the Thames River. Measurements of electrical conductivity, temperature, and salinity versus depth were made in the navigation channel at 16 locations between New London Ledge Light and the tidal basin at Norwich on 26 days between 5 July 1968 and 9 June 1969. The results of these measurements are presented here in terms of salinity distribution along the length of the river as a function of the amount of freshwater discharge into the estuary. The variation of salinity stratification along the river is shown for several values of freshwater discharge, and a rough estimate of the flushing time of the estuary is presented for a very limited case.

DESCRIPTION OF THE THAMES RIVER ESTUARY

The Thames River, located in the southeastern corner of Connecticut, is one of four major estuaries opening into Long Island Sound. Of the four, it ranks third in volume of fresh water discharged into the Sound with a two-year mean (1968-1969) of 6.3 million cubic meters per day (m^3/day), compared with 48.4 million m^3/day from the Connecticut River, 8.3 million m^3/day for the Housatonic River, and less than 1 million m^3/day from the tributaries of New Haven Harbor. The combined average discharge into the Sound from all other streams is approximately 4 million m^3/day.[10]

Figure 1 is an outline of the Thames River and its tributaries. The Thames River estuary extends from Long Island Sound to the tidal basin at Norwich, a distance of approximately 16 statute miles (25.8 km), measured along the center of the navigation channel between New London Ledge Light (Site 1) and Norwich Basin (Site 16).

The several small streams along the length of the Thames River, which have a total rainfall drainage area of about 60 square miles, contribute relatively little fresh water to the estuary. The major tributaries are the Shetucket River and the Yantic River, both entering the Thames at Norwich. A few miles north of Norwich, the Quinebaug River joins the Shetucket River. The drainage areas of the three

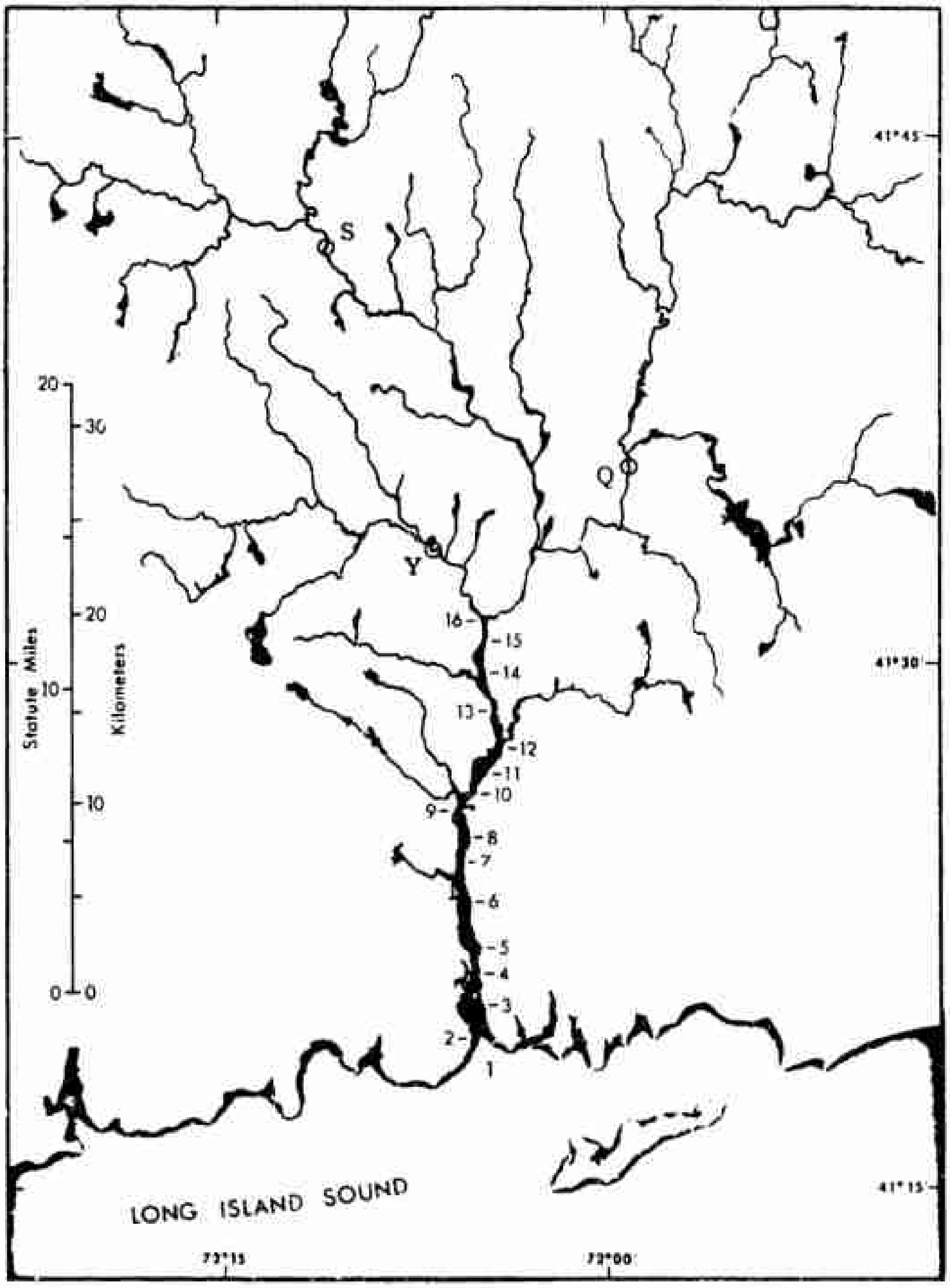

Fig. 1. Drainage Areas of Tributaries of the Thames River. (Three of the stream-gaging stations operated by the U. S. Geological Survey are designated by letters: S-Shetucket River, Q-Quinebaug River, and Y-Yantic River. The numbers 1 through 16 designate the 16 conductivity-temperature measurement sites along the Thames River from New London to Norwich.)

major river basins feeding the Thames River are 743 sq mi for the Quinebaug, 514 sq mi for the Shetucket, and 88 sq mi for the Yantic River Basin. Figure 1 shows all of the Yantic River Basin but includes only 35 percent (260 sq mi) of the Quinebaug River Basin and 50 percent (257 sq mi) of the Shetucket River Basin.

The combined discharge of these three rivers, as measured by the stream-gaging stations at points Q, S, and Y (See Fig. 1), accounts for an average of 80 percent of the total amount of freshwater discharge from the Thames River into Long Island Sound. The remaining 20 percent is contributed by the portions of the Shetucket and Quinebaug River Basins downstream from gaging stations Q and S and by the several small streams entering the Thames River below Norwich (See Table 1).

Table 1

DRAINAGE AREAS OF TRIBUTARIES OF THE THAMES RIVER

Stream Gaging Station*	River Name and Location	Drainage Area (sq mi)	Reference
1270	Quinebaug River at Jewett City	743	Ref. 5, p. 1
1225	Shetucket River at Willimantic	514	Ref. 6, p. 1
1275	Yantic River at Yantic	88.6	Ref. 7, p. 16
1277	Trading Cove Brook near Thamesville	8.7	Ref. 7, p. 16
1277.4	Stony Brook near Uncasville	7.2	Ref. 8, p. 48
1277.5	Oxoboxo Brook near Montville	10.2	Ref. 7, p. 16
1277.6	Hunts Brook at Quaker Hill	11.3	Ref. 7, p. 16
1277.35	Billings-Avery Brook near Poquetanuck	2.77	Ref. 7, p. 16
–	Joe Clark Brook at Poquetanuck	3.15	Ref. 8, p. 50
1277.25	Shewville Brook at Shewville	11.7(+3?)	Ref. 7, p. 16
1277.3	Crawley Brook at Poquetanuck	2.24	Ref. 7, p. 16
(1277.31)	Halls Brook at Poquetanuck (combines 1277.25 and 1277.3)	17(?)	–

*In Fig. 1, stations 1270, 1225, and 1275 are represented as Q, S, and Y, respectively.

The volume of fresh water discharged into the estuary is usually very small compared with the huge volume of sea water transported in and out of the estuary by the tides,* and during most of the year the waters of the Thames River are

Table 2

SURFACE AREA OF THE THAMES RIVER**

Segment (See Fig. 14)	From — to:	Latitude	Surface Area (km^2)
	Mouth of Thames River (Line connecting New London Harbor Light and Eastern Point, Groton)	41° 19.1'	
A			5.23
	Railroad bridge	41°21.8'	
B			3.19
	North end of wide dredged area	41°24'	
C			2.55
	Overhead power cable crossing	41°26.3'	
D			2.93
	Mohegan-Pequot Bridge	41°28.9'	
E			1.53
	Norwich	41°31.4'	
		Total	15.43 km^2

**Measured from Coast and Geodetic Survey Chart 359, "Thames River and New London Harbor, Long Island Sound to Norwich."

	Mean High Water (ft)	Mean Tide Level (ft)	Mean Low Water (ft)	Extreme Low Water (ft)
New London	2.6	1.3	0.0	-3.5
Norwich	3.1	1.5	0.0	-3.5

*The mean volume of the tidal prism was calculated to be $13.3 \times 10^6 m^3$, based on a river area of 15.4 km^2 (Table 2) and mean-high-water to mean-low-water difference of 2.6 ft (0.79 m) at New London and 3.1 ft (0.94 m) at Norwich.

usually of relatively high salinity throughout its length. A study of the salt water intrusion into coastal river basins (Fig. 28 in Ref. 7) shows that during periods of low stream flow the upper limits of the salt water can extend almost two miles up along the bottom of the Shetucket River and nearly one mile up along the bottom of the Yantic River. When high freshwater inflow occurs, however, the effects of the stream discharge become significant, and at low tide the freshwater flow may push the head of the salt wedge several kilometers downriver.

METHODS

The electrical conductivity and the temperature of the Thames River waters were measured in situ with a Beckman Instruments Type RS5-3 Electrodeless Induction Salinometer. The conductivity-temperature cell of this instrument was lowered by its cable over the side of a stationary boat drifting in the channel, and a set of measurements was made at each of several depths at each site. The measurement sites were chosen to be next to channel buoys or near obvious landmarks to facilitate bringing the boat quickly to the same location each time. All of the measurements were made in the navigation channel, usually at the side of the channel nearest the navigation buoy. The cross-sectional profiles of the river shown in Fig. 2 were made with a portable fathameter in a small boat during near low tide at each of the measurement sites. A list of the sites and their locations is given in Table 3.

The dial readings of conductivity, temperature, and salinity were recorded manually on a data sheet and were later plotted against depth for each of the measurement sites. These graphs are included in this report as Appendix A. It should be pointed out here that the quantities that were actually measured were the electrical conductivity and the temperature of the river water. The so-called "salinity" value is a derived quantity that depends on the resistance of the thermistor in the conductivity-temperature cell and on the resistance needed to balance the conductivity bridge in obtaining the conductivity reading.[11] For measurements in sea water, the salinity dial reading quite accurately represents the salinity of the water. In regions where there is significant mixing of fresh and salt waters, however, it is not really valid to consider the "salinity" dial readings as being representative of the true value of salinity. Salinity is a defined characteristic of sea water that depends mainly on the chlorinity of the sea water.[12] As the sea water becomes diluted by river water, carbonates and electrolytes such as organic acids contribute to the conductivity, producing an indication of a higher salinity than is the case. For the purpose of this report, however, this error is small. From a graph (Fig. 6 in Ref. 13) of salinity versus the fraction of sea water in a mixture of sea water and river water, it is seen that a salinity reading of 0.2‰ would be 200 or 300 percent too high; a reading of 1‰ would be approximately 10 percent too high; but for salinities greater than 3‰ there is probably no significant error at all.

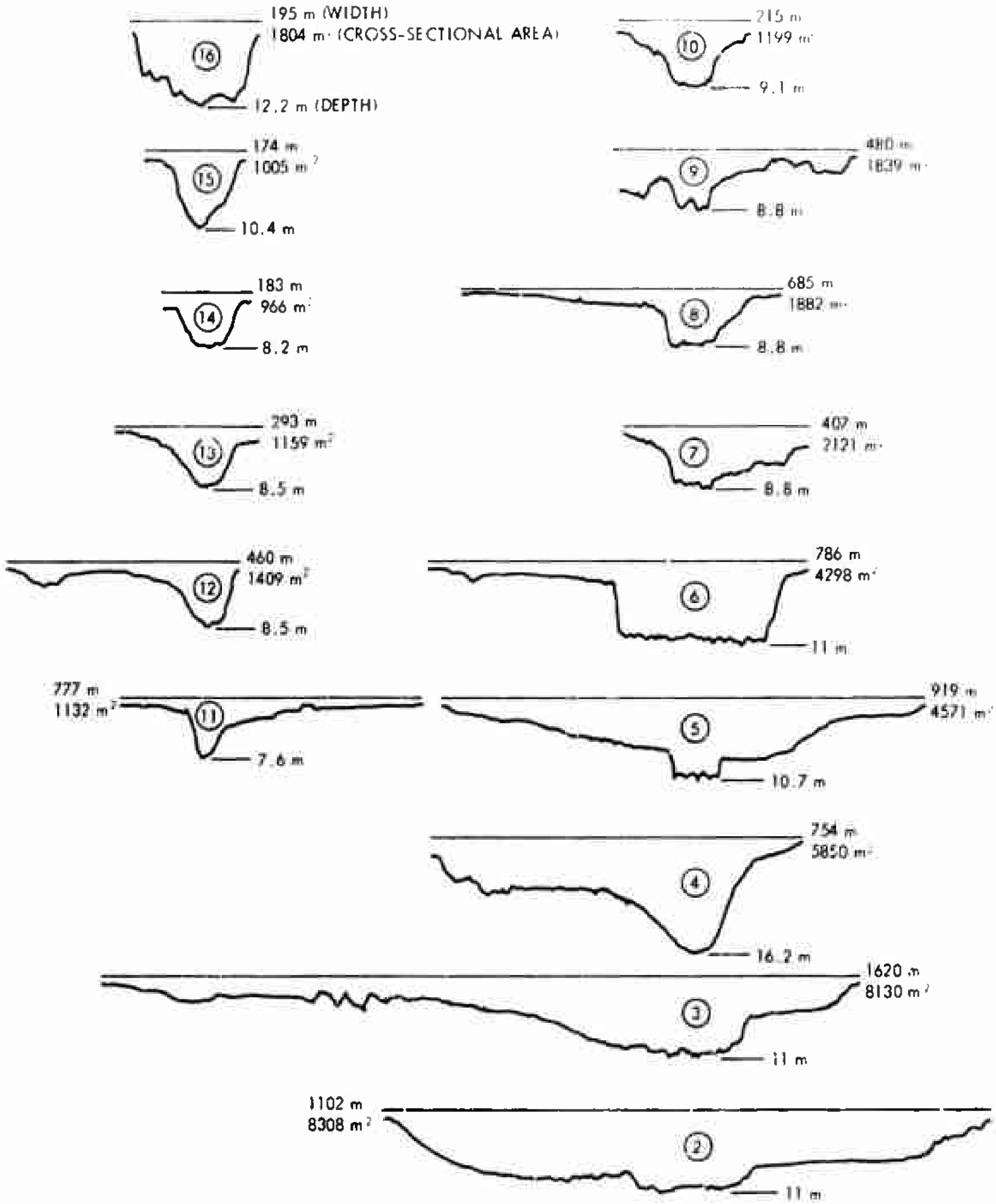

Fig. 2. Transverse Depth Profiles at 15 of the 16 Measurement Sites along the Thames River Viewed Upriver with the West Side to the Left and the East Side to the Right. (The vertical exaggeration of depth is approximately 14:1. River width, maximum depth, and cross-sectional area are given for each measurement site. The locations of sites are listed in Table 3.)

Table 3

LOCATION OF MEASUREMENT SITES IN THE THAMES RIVER*

Site No.	Approximate Latitude	Nearest Buoy or Landmark	Distance between Site and Norwich Basin (km)	Interval (km)
1	41° 18.3'	New London Ledge Light	25.8	
				1.3
2	41° 19.3'	Buoy "6"	24.0	
				1.9
3	41° 20.3'	Buoy "8"	22.1	
				1.6
4	41° 21.2'	Buoy "12"	20.5	
				1.4
5	41° 22'	Buoy "2"	19.1	
				2.3
6	41° 23.2'	Buoy "8"	16.8	
				2.3
7	41° 24.3'	Buoy "1"	14.5	
				1.4
8	41° 25.1'	Buoy "5"	13.1	
				1.4
9	41° 25.8'	Yale Boathouse	11.7	
				1.3
10	41° 26.3'	Center of overhead power cables	10.4	
				1.2
11	41° 26.9'	Buoy "14"	9.2	
				2.0
12	41° 27.6'	Buoy "20"	7.2	
				2.0
13	41° 28.7'	Buoy "26"	5.2	
				2.4
14	41° 29.8'	Buoy "33"	2.8	
				1.7
15	41° 30.7'	Buoy "40"	1.1	
				1.1
16	41° 31.2'	Approximate center of Norwich Basin	0	

*See Coast and Geodetic Survey Chart No. 359.

At the outset of this measurement program, the intent had been to make a complete set of measurements along the Thames River on a nearly biweekly basis. The days on which the data were to be taken were those on which high tide at the Connecticut State Pier occurred at noon, plus or minus an hour or so. Data were also to be obtained on some of the days during which low tide at State Pier occurred at or near noon. The choice of high- and low-tide days was an arbitrary one, but it was made in order to avoid, as much as possible, the variations due to tidal effects It was also intended that there would be one or more sets of data taken at two sites (4 and 10) covering a 13-hour period to provide frequent observation of the

short-term variations of salinity, temperature, and electrical conductivity throughout a complete tidal cycle. As it turns out, there were 26 successful river cruises between 5 July 1968 and 9 June 1969 (See Appendix B), of which 13 were made during a period of low tide plus or minus 2-1/2 hours and 13 during a period of high tide plus or minus 3 hours (See Appendix C, Table C-5). No 13-hour tidal-cycle measurements were carried out during this measurement series.

UPLAND FRESHWATER DISCHARGE

During periods of high stream flow, the amount of freshwater discharge into the Thames River estuary strongly influences the salinity distribution in the river. As mentioned before, one measure of freshwater discharge into the Thames is the sum of the stream flow values measured at stream gaging stations in the major tributaries. The United States Geological Survey office in Hartford, Connecticut, provided the stream flow records for 1968 and 1969 of the daily readings at stream gaging stations on the Shetucket River at Willimantic, the Quinebaug River at Jewett City, and the Yantic River at Yantic. Using these records, we calculated the daily total values for these three stations for the period of interest of this report (Appendix C) and plotted the values as discharge rate versus date (Fig. 3). According to calculations by USGS personnel, the sum of the values measured at these three stations generally represents about 80 percent of the total freshwater discharge into the Sound. In this report, the sum total of the values measured at these three stations (Q, S, and Y, shown in Fig. 1) is used as an arbitrary reference number in connection with the salinity profiles; no attempt is made to correct for the actual values of freshwater discharge into the river except in the computations of the flushing time. Various averages were computed for the readings at each of these gaging stations for the several days preceding the date of measurement (See Appendix C) to determine the correspondence between these readings and the salinity profiles of the river. It appeared that the fresh/salt structure was somewhat better related to the average gaging station readings for the two days preceding the date of measurement than to any of the other choices, so this is the value chosen for use with the graphs presented below (Figures 6 through 15).

The freshwater discharge data are also presented in Fig. 4 in terms of the percentage of time that the discharge values were exceeded versus the discharge values themselves. It can be seen that during the period of interest the total discharge for the three stations was at least 1341 ft^3/sec for 50 percent of the time. The discharge was greater than 176 ft^3/sec 99 percent of the time, but it exceeded 9980 ft^3/sec only 1 percent of the time.

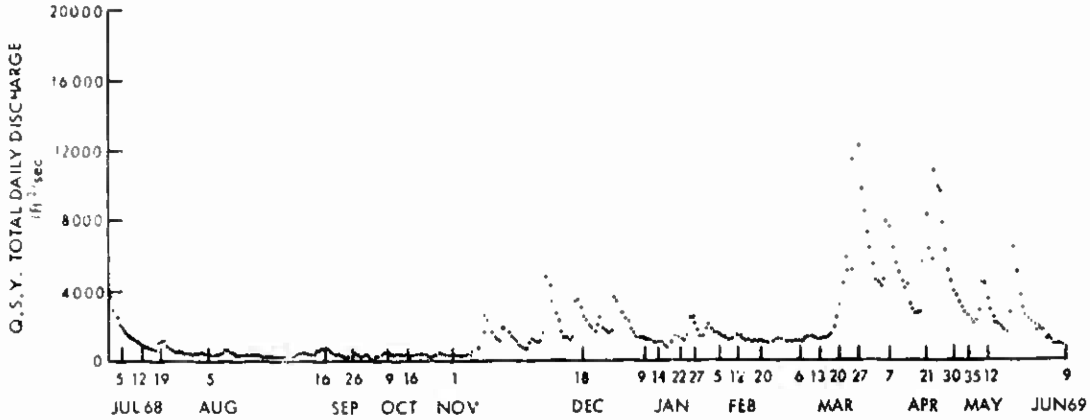

Fig. 3. Total Daily Discharge of the Three Major Tributaries as Measured at Gaging Stations Q, S, and Y in Fig. 1. (These values represent approximately 80 percent of the actual freshwater discharge from the Thames River into Long Island Sound. The remaining 20 percent is contributed by the runoff downriver from each of the gaging stations and by several small streams entering along the sides of the Thames River.)

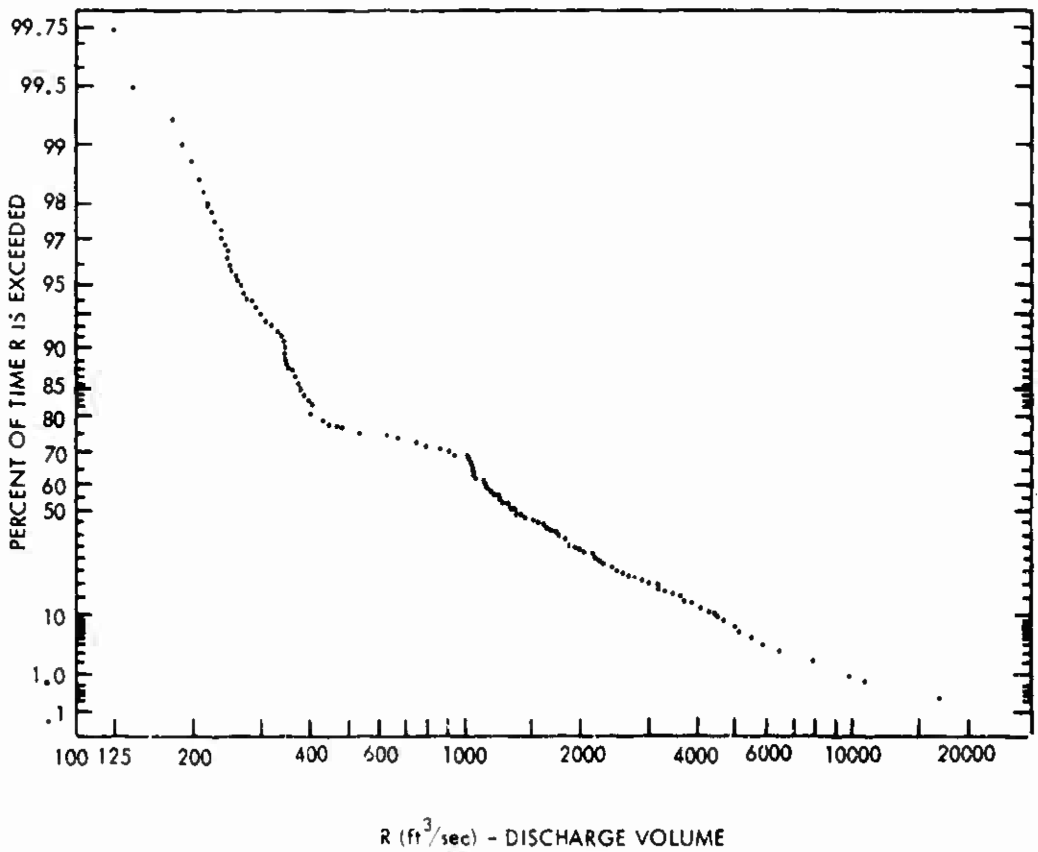

Fig. 4. Exceedance Curve for the Daily Total Freshwater Discharge Measured at Gaging Stations Q, S, and Y. (To obtain discharge values in m³/sec, multiply value in ft³/sec by 0.02834. Note that the arithmetic average (2244 ft³/sec) for the period of interest occurs at the 36-percent exceedance level.)

RESULTS

Only the general results of the observations of electrical conductivity, temperature, and salinity in the Thames River are discussed here. The detailed results are presented graphically in Appendix A. One of the authors (ABB) has also computed and plotted the sound-velocity profiles associated with the conductivity, temperature, and salinity conditions for 14 of the 26 days. These graphs are presented in Appendix D.

TEMPERATURE

Figure 5A shows the variation through the year of the temperature of two selected portions of the river: the deeper waters of New London Harbor and the near-surface waters of the upper estuary. The temperature of the deeper half of the body of salt water in the harbor varied almost sinusoidally through the year, ranging from a high of 19.5°C during early September to 1.1°C during early March, with an estimated mean for the year of 10.4°C. Crossings of the mean value (extrapolated) occurred in early December and early June. The temperature of the fresher water overlying the salt wedge in the upper reaches of the river reflects the influence of seasonal land and air temperatures. The temperature of this surface water was found to be nearly the same as that of the underlying salt water during the winter, being a degree or two colder during January and February and a degree or so warmer than the salt water during March. When the spring rains came, however, the temperature differential between the fresh surface waters and the underlying salt water increased steadily from a difference of 5.6°C on 7 April to 7.6°C on 5 May 1969, then dipped to a difference of 5.2°C on 12 May before increasing further to 8.1°C on 9 June 1969. During the preceding July, the freshwater temperature exceeded the salt-water temperature by 7.5 to 10°C.

ELECTRICAL CONDUCTIVITY

The values of electrical conductivity for the salt water also varied almost sinusoidally, having a maximum in early September of approximately 42 millimhos per centimeter (mmhos/cm) and a minimum in early March of about 26 mmhos/cm (Fig. 5B). The near-surface waters of the upper reaches of the river had conductivity values ranging from a maximum of 26 mmhos/cm on 9 October 1968 (Site 13) when there was low freshwater discharge and high water temperature, down to less than 1 mmho/cm during periods of significant amounts of freshwater discharge.

SALINITY

Figure 5C shows the variation through the year of the sea water salinity in the lower depths of the channel in New London Harbor at Site 2. The salinity of the deeper half of this body of sea water was found to lie between 31.3 and 31.5‰ during periods of low freshwater discharge, falling to as low as 29.3‰ (5 May 1969) during the spring rains.

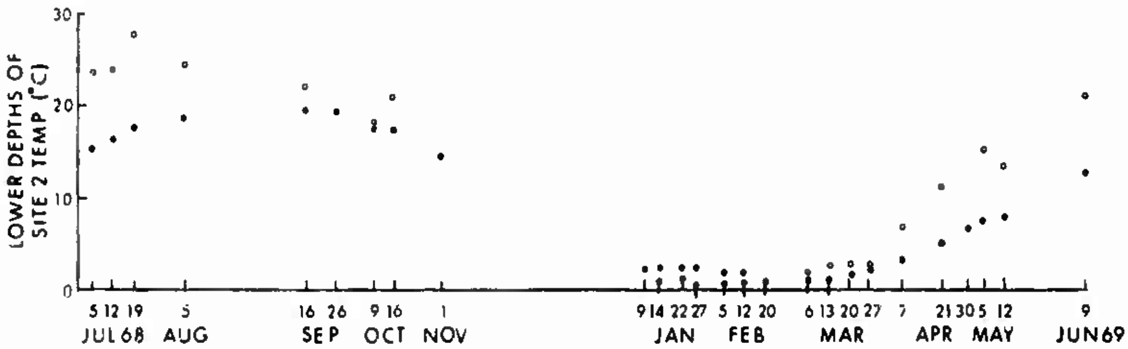

Fig. 5A. Temperature Variation through the Year

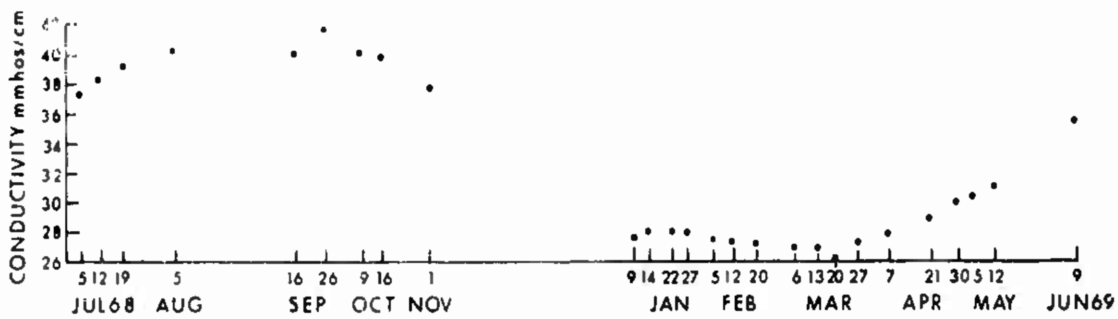

Fig. 5B. Electrical Conductivity Variation through the Year

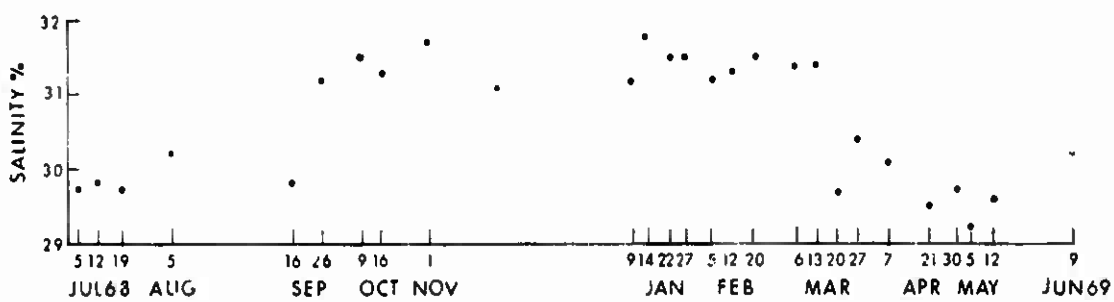

Fig. 5C. Salinity Variation through the Year

Fig. 5. Graphs of Temperature, Electrical Conductivity, and Salinity for the Deepest Portion of the Salt Wedge in New London Harbor (at Site 2), Plotted as Functinns of Date of Measurement. (Figure 5A also shows the temperature variation of the near-surface waters in the upper reaches of the estuary, indicated by the open circles.)

At some places along the river, near the outfalls of some of the larger industrial power plants, plumes of warmer water have been observed at various subsurface depths. Studies of the shape, extent, and duration of these plumes require measurements of finer spatial and temporal resolution than those reported here. Indications of such plumes are seen in the temperature curves of the following figures in Appendix A:

Figure	Site
A-5	7, 8, 9, 10, and 11
A-8	8 and 9
A-13	9 and 10
A-16	7
A-17	9
A-18	3 and 9
A-19	8 and 9

Indication of a subsurface temperature maximum did not necessarily result in the appearance of a subsurface conductivity maximum because the delay between readings of temperature and conductivity (approximately one-half minute) allowed time for the boat to drift away from the plume or for the plume to shift position (a matter of a few meters).

The occurrence of a subsurface temperature maximum was also observed in the data obtained in the thermal structure survey mentioned in the Introduction. The following information was released through the courtesy of Mr. Daniel T. Hedden, Northeast Utilities Service Company, Hartford, Connecticut[3]:

> The portion of the Thames River in the vicinity of the Montville electric power plant was intensively surveyed during the period August 12 to September 24, 1968, to determine the temperature distribution in the river and the relationship of the temperature to the volume of heated coolant water being discharged from the plant. In the course of these measurements, which were made for the Northeast Utilities Service Company by the Marine Research Laboratory (Raytheon), indications were found of a sub-surface temperature maximum which extended over a limited region in the vicinity of the coolant discharge point. W. Owen has proposed the following mechanism to explain this sub-surface temperature maximum. It appears that the cooling water for the power plant is taken from waters below the halocline, and is heated by passage through the plant, then discharged (at a shallower depth) into the fresher water above the halocline. Even though the heated discharge water is warmer than the surface water, it is more dense and it sinks to its own density level, producing a

sub-surface temperature maximum in a stable density profile. The location of the sub-surface maximum upstream or downstream from the discharge point varied with the tide phase, but maintained its identity for a significant length of time before being dissipated. (Personal communication, Wadsworth Owen, July 1969.)

SALINITY PROFILES OF THE THAMES RIVER

The data on salinity versus depth were used to develop longitudinal profiles of salinity distribution as a function of location along the length of the river. A computer program was used to perform a linear interpolation between depths, and the resulting contours of constant salinity were printed out on a Calcomp plotter.

The longitudinal profiles of salinity distribution along the river are shown in chronological order in Figs. 6 through 12. The numbers associated with the contours represent values of salinity in parts per thousand. The ordinate values represent depth in meters below the river surface. Along the right-hand margin are the date of measurement, the time of occurrence of high or low tide at the Connecticut State Pier (near Site 4), and the combined value of freshwater discharge at gaging stations Q, S, and Y averaged over the two days preceding the date of measurement. The measurement site numbers are shown along the abscissa, and the time of measurement at each site are shown along the top of each individual profile. (The times shown are local times: Eastern Standard Time for the data taken from 1 November 1968 through 21 April 1969, and Eastern Daylight Time otherwise.) The outline of the river bottom does not represent the channel center depth but rather is the bottom depth at the point of measurement, generally to one side or the other of the center of the channel. (The measured midchannel depths are shown in Fig. 2.) At the top of each page, a map of the river reflects the surface salinity distribution for the topmost profile in each figure.

To allow visual comparison between profiles, the dividing line between the salt water and the overlying fresh water was chosen to be the salinity contour representing a value of ten parts per thousand. That this is a reasonable choice may be seen by referring to the salinity versus depth graphs of Appendix A. The 10 parts per thousand value is the point at which the salinity value has decreased to approximately 1/e (or about 37 percent) of the maximum salinity value measured at a given site.

The large vertical exaggeration (250 : 1) gives an impressionistic view of what happens to the fresh/salt structure for various values of freshwater discharge. The

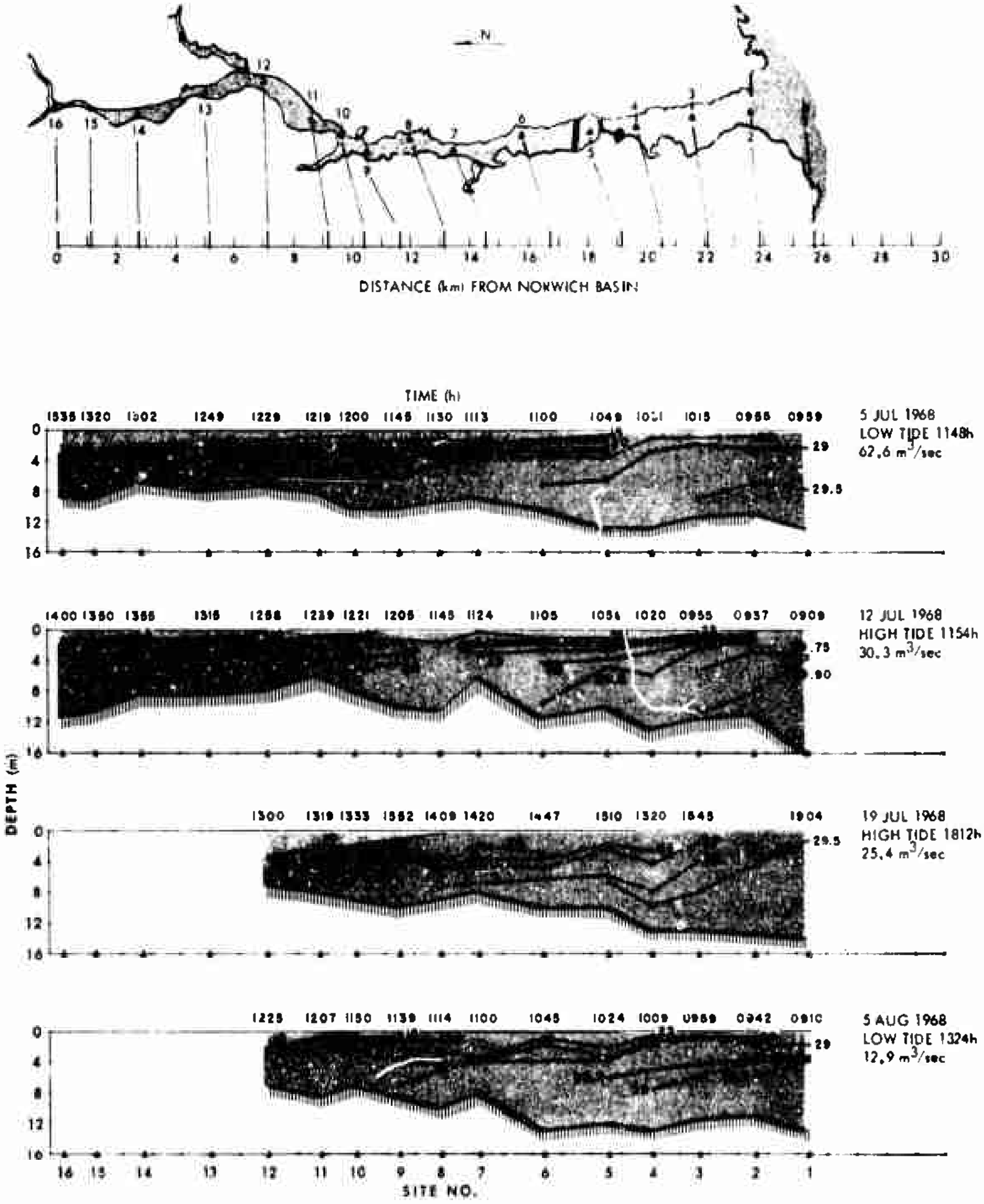

Fig. 6. Salinity Profiles of the Thames River for 5, 12, and 19 July and 5 August 1968

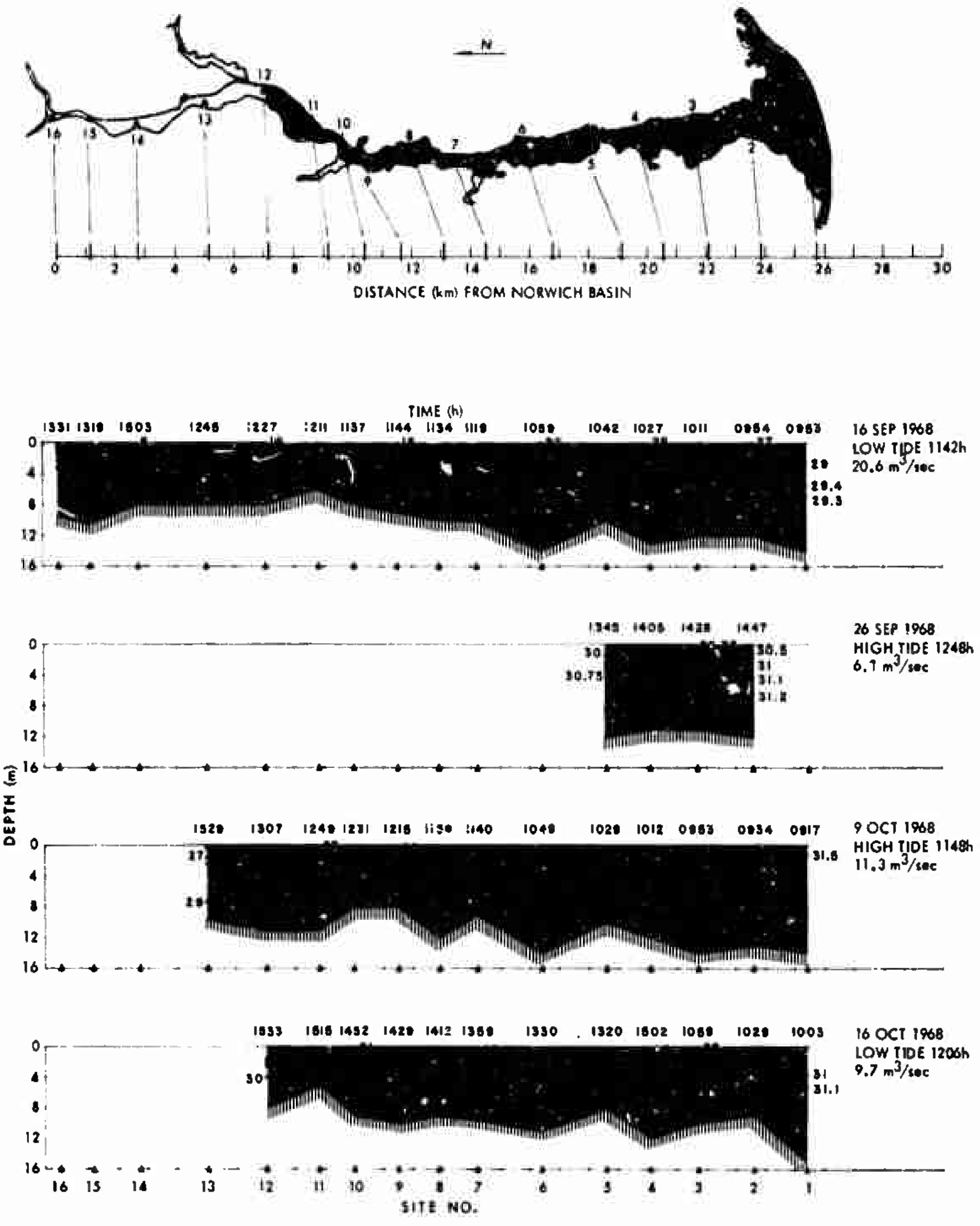

Fig. 7. Salinity Profiles of the Thames River for 16 and 26 September and 9 and 16 October 1968

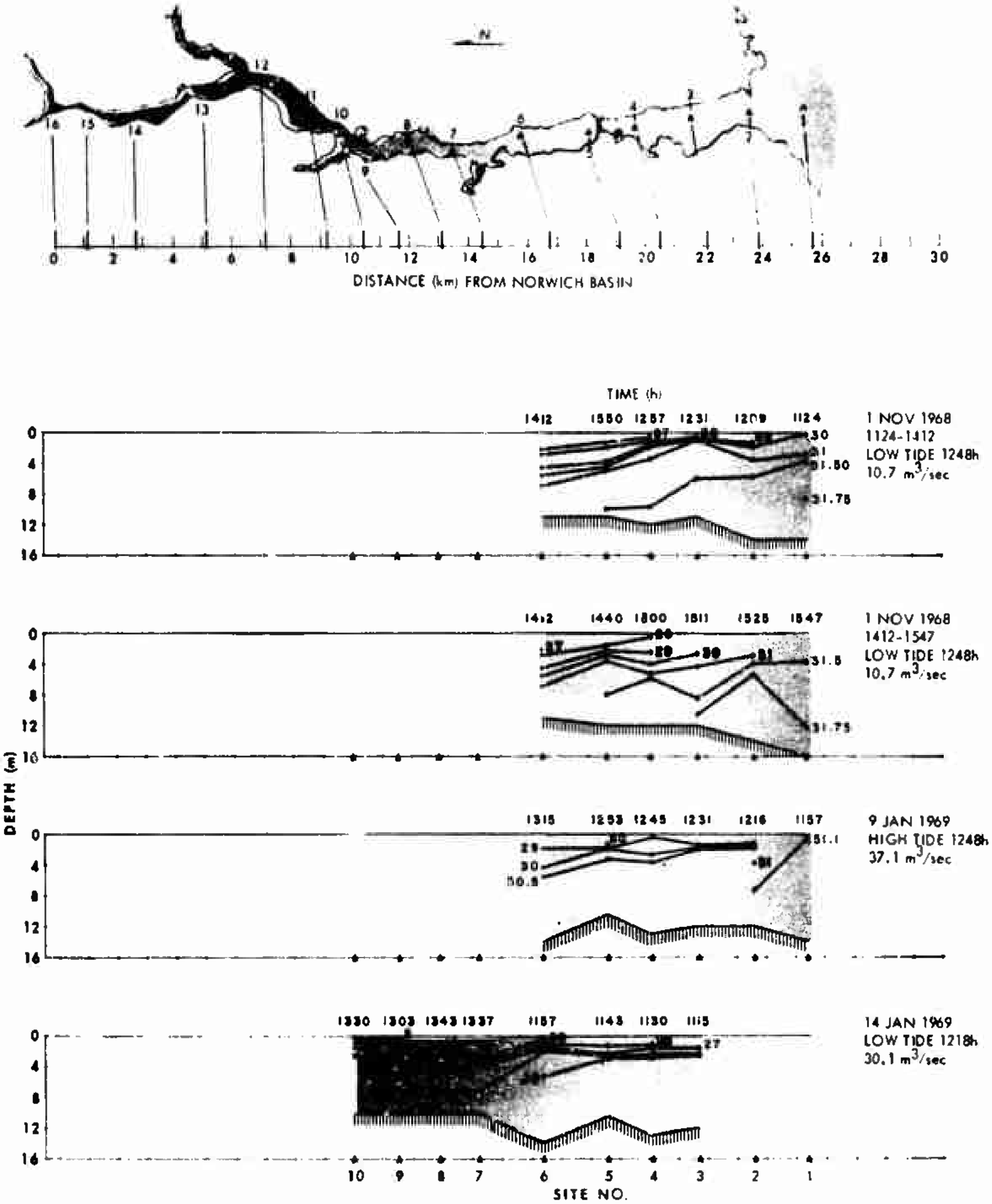

Fig. 8. Salinity Profiles of the Thames River for 1 November 1968 and 9 and 14 January 1969

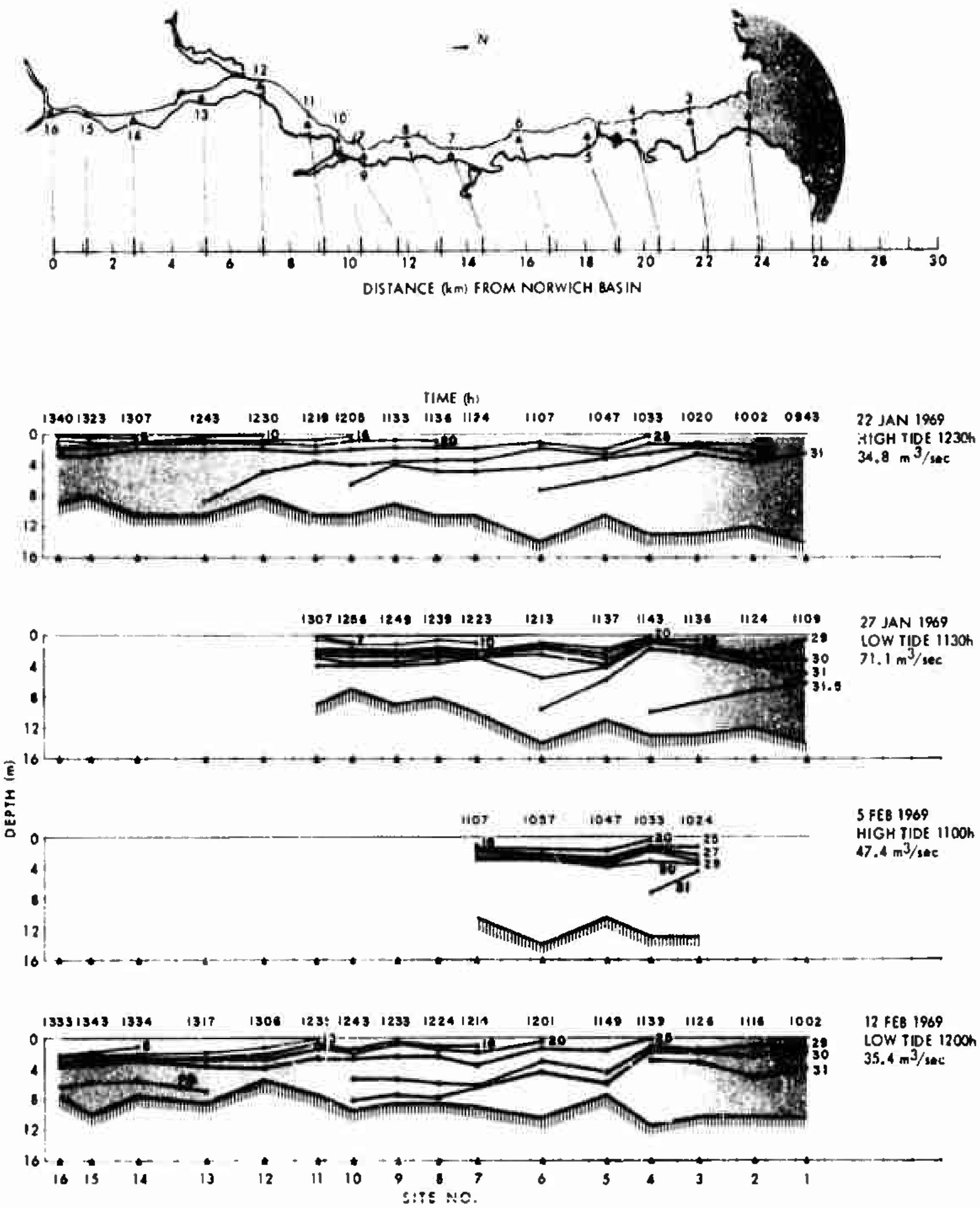

Fig. 9. Salinity Profiles of the Thames River for 22 and 27 January and 5 and 12 February 1969

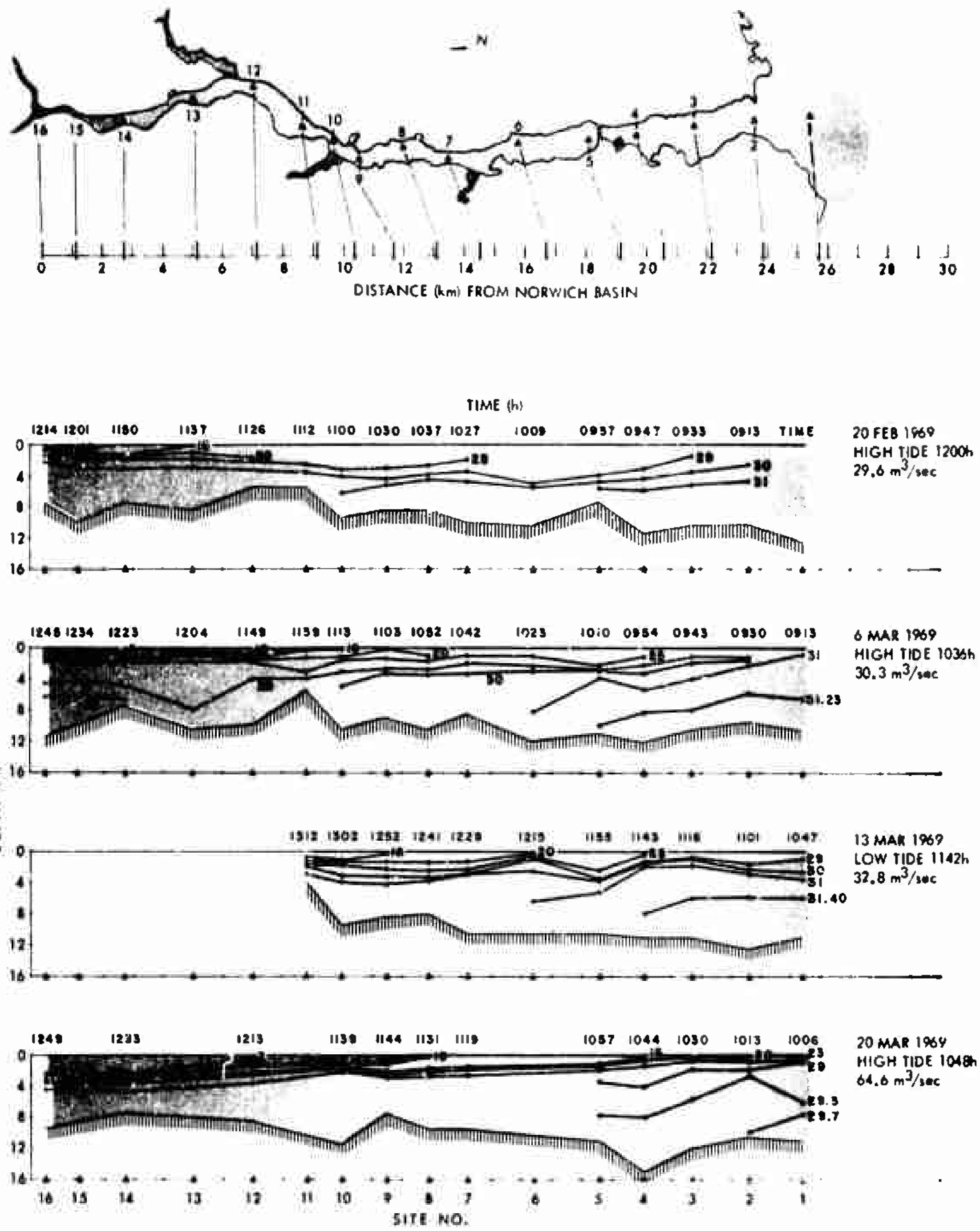

Fig. 10. Salinity Profiles of the Thames River for 20 February and 6, 13, and 20 March 1969

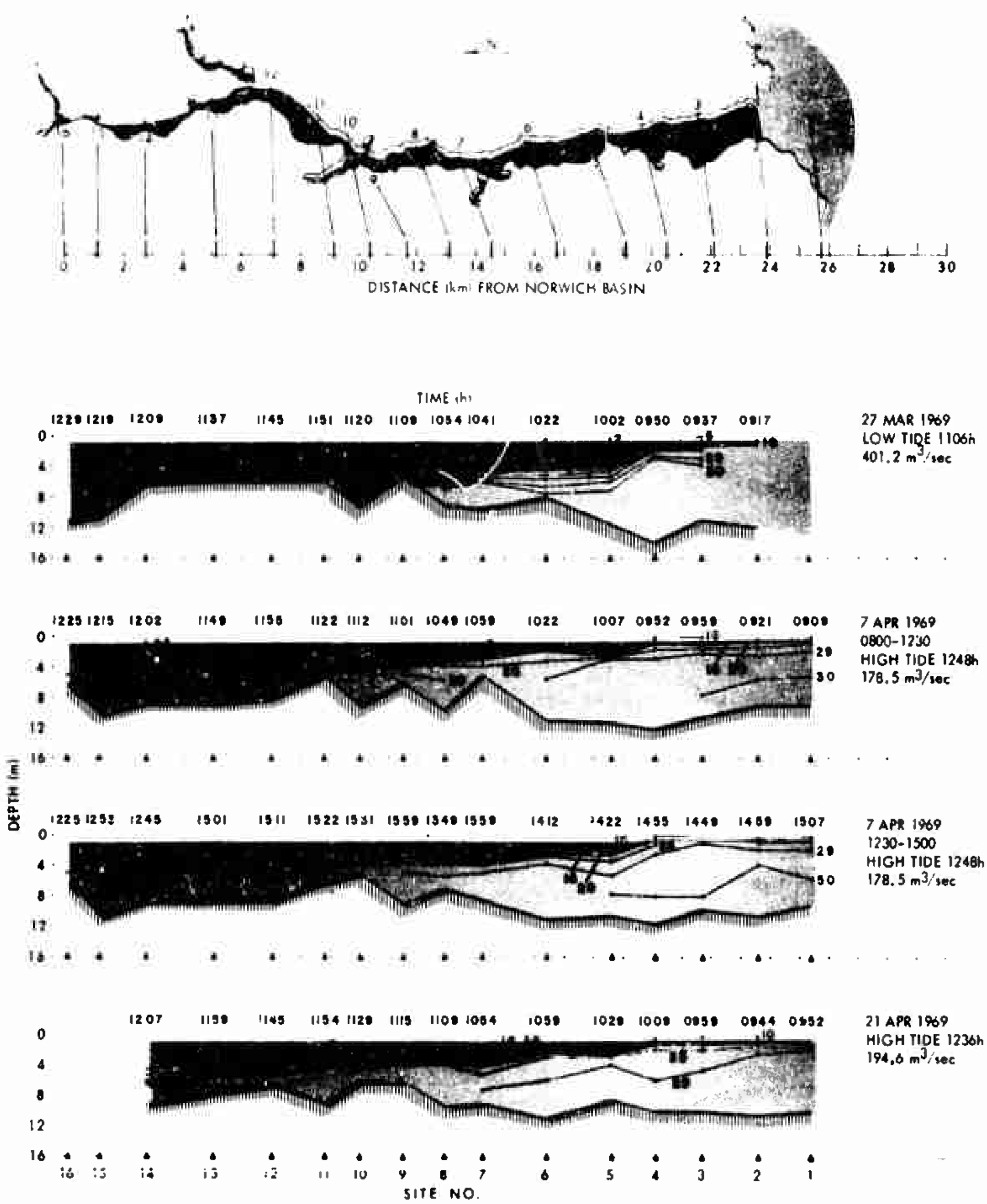

Fig. 11. Salinity Profiles of the Thames River for 27 March and 7 and 21 April 1969

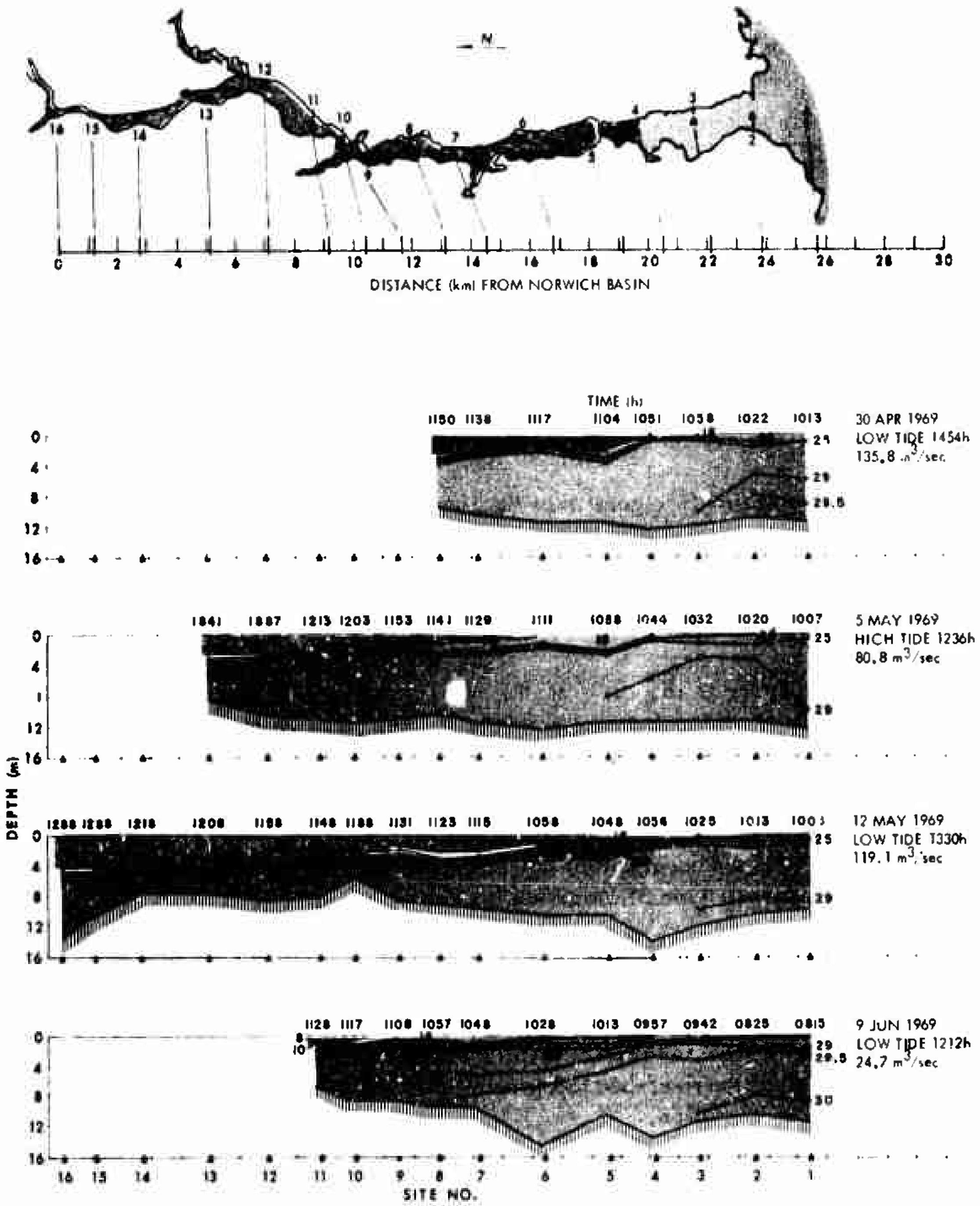

Fig. 12. Salinity Profiles of the Thames River for 30 April, 5 and 12 May, and 9 June 1969

effect of the freshwater discharge upon the salinity distribution in the river becomes quite apparent as one scans the successive profiles and their accompanying discharge values.

SALINITY STRATIFICATION

The salinity profiles above indicate that the Thames River is primarily a salt-water inlet whose structure is modified by the freshwater inflow from its tributaries. The amount of freshwater discharge varies so widely that a classification of the river according to its estuarine type could range from that of a two-layer flow type to a salt-wedge type of estuary.[14] From the nature of the data, it appears reasonable to classify this river as basically a two-layer flow type with entrainment and with varying degrees of mixing taking place, depending upon the river's cross-sectional outlines (thus, the current velocity profiles) found along the length of the river.

Hansen and Rattray[15] suggest that the classification of an estuary be based on its salinity stratification and circulation, where

a. Salinity stratification is the ratio of the top-to-bottom salinity difference to the mean salinity over a transverse cross section of the river at some point along its length, and

b. Circulation is the ratio of the net surface current velocity to the mean freshwater velocity through the cross section.

When data on surface current velocity are lacking, as is the case here, only the mean freshwater velocity through the section can be obtained (mean freshwater velocity = freshwater discharge ÷ cross-sectional area of the river). The net surface current velocity is unknown so that the circulation parameter can not be determined, and a Hansen-Rattray type of classification can not be defined.

It is of interest, however, to plot salinity stratification versus location along the length of the river for various values of freshwater discharge. Figure 13* shows the salinity stratification curves for data taken during periods of flooding and high tide, and the curves of Fig. 14* represent data taken during periods of ebbing and low tide. The effects of the river-bed topography upon the stratification become apparent in this type of presentation.

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*The number beside each curve in Figs. 13 and 14 is the rate (in cubic meters per second) of freshwater discharge for the combined readings at the three gaging stations (Q, S, and Y) averaged over the two days preceding the date of measurement.

Consider the stretch of river between Sites 7 and 4 (See Figs. 13 and 14). The river leaves the narrow channel at Site 7, broadens out into the wide turning basin at the Submarine Base and continues on down past Site 6 until it meets the constriction at the bridges below Site 5, then broadens out again into New London Harbor. During ebbing and low tide (Fig. 14), the salinity stratification values decrease smoothly past Sites 7, 6, and 5. The stratification value drops sharply at Site 4, suggesting that passage through the constricted region at the bridge has brought about a significant degree of mixing of the river waters. During flood tide, the incoming sea water apparently piles up at the constriction near the bridges, thereby impeding the downstream progress of the fresher waters of the river. The ratio of fresh water to salt water just above the bridges increases so that the mean salinity in that area is reduced, and this is indicated by the increased salinity stratification values at Site 5 (Fig. 13).

Effects of the constriction at Site 10 are also apparent. During flooding and high tide, the salinity stratification values are always lower at Site 10 than they are at Site 11 because, while the subsidence of the underlying sea water has increased the ratio of fresh water to salt water at Site 10, the subsidence of the level of salt water at Site 11 has been impeded by the constriction of the river at Site 10, and the change in stratification value at Site 11 is retarded.

In general, for the river as a whole, it may be observed from Figs. 13 and 14 that for a given value of freshwater discharge, the salinity stratification values are approximately 30 percent higher during periods of ebbing and low tide than they are during flooding and high tide.

FLUSHING TIME

One of the characteristics of the Thames River Estuary which may be approximately calculated from the data presented above is the time required for a pollutant to be flushed out of the river for various values of freshwater discharge. Various methods have been used for calculating flushing times in estuaries,[16] but in this brief section we shall simply follow the treatment given by Bowden[14] to obtain a relation between flushing time and freshwater discharge for a very special case. The assumptions are (1) that the pollutant is introduced into the water at the head of the estuary, and (2) that the density of the pollutant is identical to that of the fresh water and is uniformly distributed in the freshwater inflow.

The flushing time, t_f is the time needed to remove an accumulated volume, F, of fresh water present at a given instant due to the rate of freshwater influx (i.e., the freshwater discharge), R. A steady state is assumed, so R also represents the rate at which fresh water is being removed from the estuary.

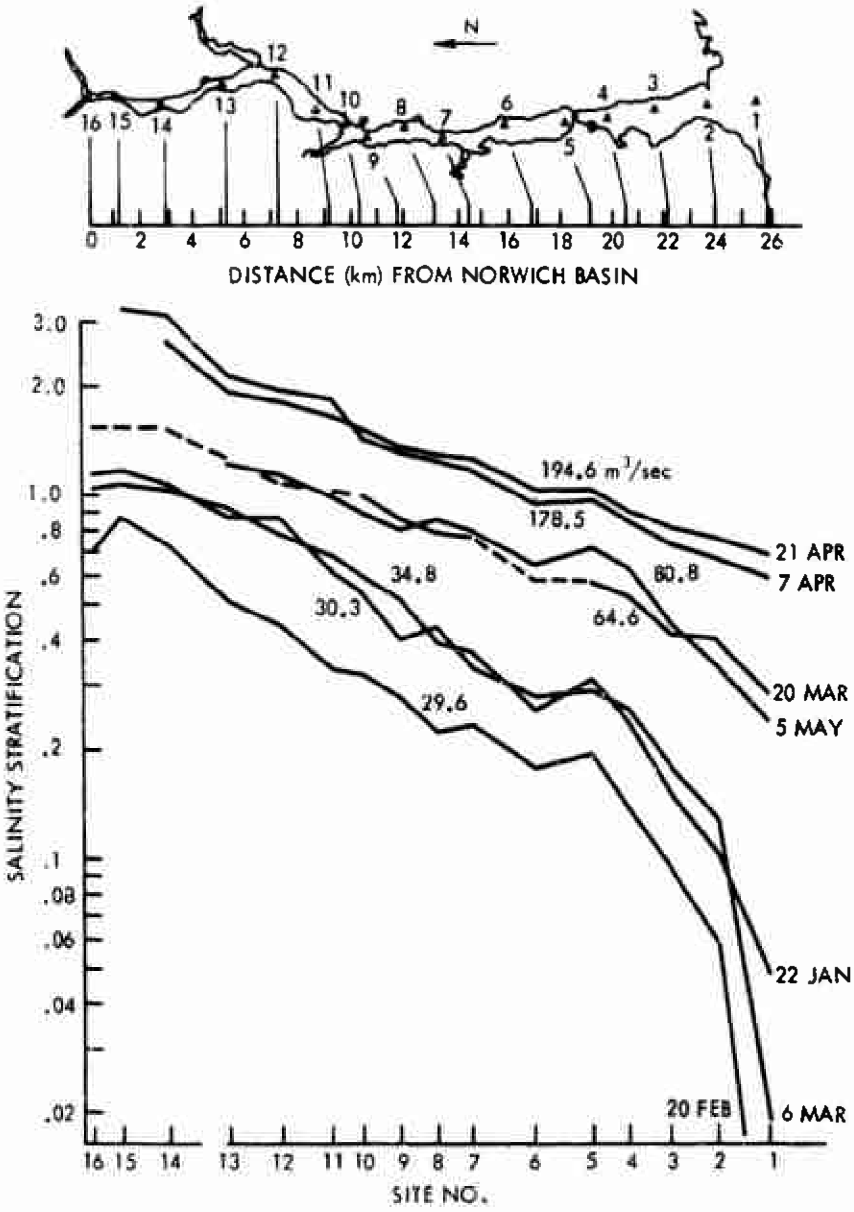

Fig. 13. Salinity Stratification as a Function of Location along the Thames River: Selected Curves of Data Taken during Periods of Flooding and High Tide. (The number beside each curve is the rate (in cubic meters per second) of freshwater discharge for the combined readings of the three stations averaged over the two days preceding the date of measurement.)

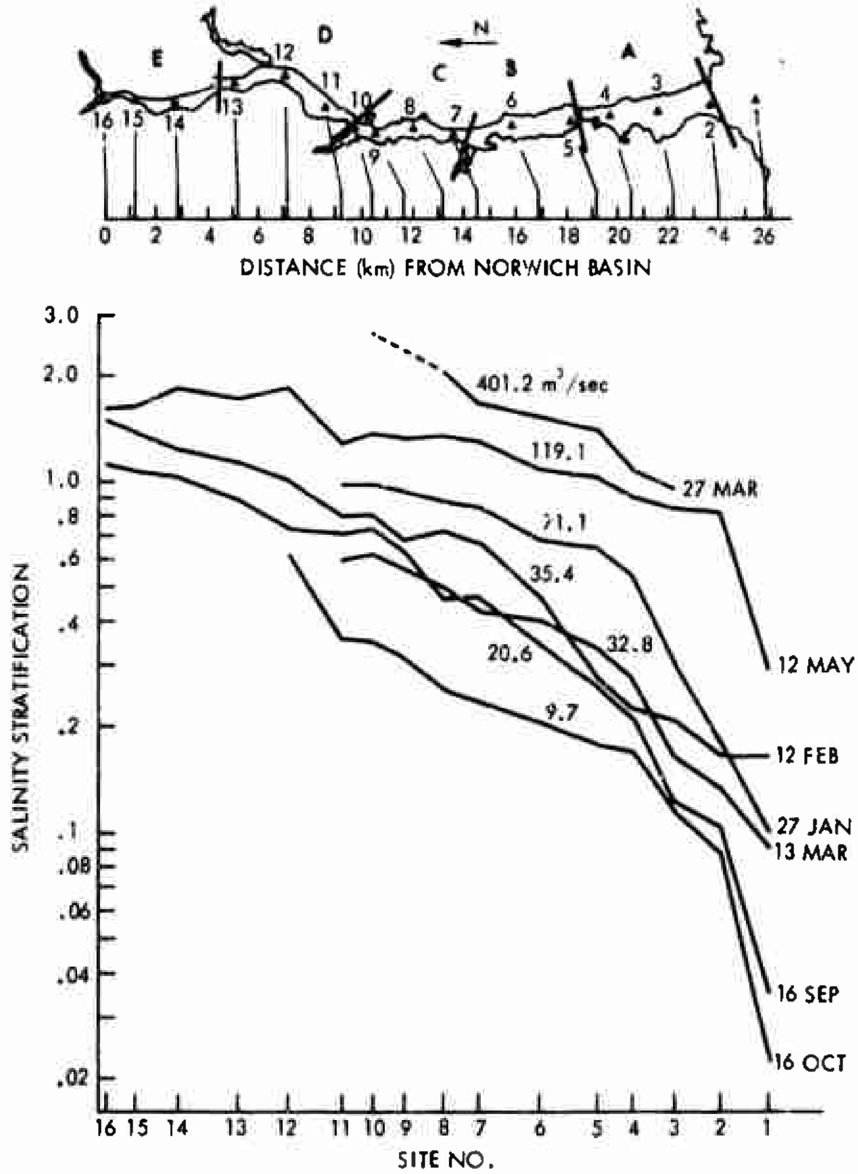

Fig. 14. Salinity Stratification as a Function of Location along the Thames River: Selected Curves of Data Taken during Periods of Ebbing and Low Tide. (The number beside each curve is the rate (in cubic meters per second) of freshwater discharge for the combined readings of the gaging stations averaged over the two days preceding the date of measurement.)

The volume of accumulated fresh water in the estuary was estimated for each of several selected days by relating the amount of fresh water ($S < 10‰$), shown in the salinity profiles (Figs. 6 through 12), to the surface area and river-bed topography (Table 2 and Fig. 2, respectively) bounding that particular volume of fresh water. The volume was then divided by the estimated value of freshwater discharge for that day to obtain the flushing time.

Figure 15 is a plot of flushing time as a function of freshwater discharge. The letter R represents the combined values of freshwater stream flow measured at gaging stations Q, S, and Y averaged over the two days preceding the data of measurement. As mentioned before, R represents approximately 80 percent ($\pm$ 6 or 7 percent) of the value of freshwater inflow that actually enters Long Island Sound. Therefore, assuming a relatively small contribution from streams along the length of the Thames River, another set of discharge values, $R' = 5/4\ R$, has been plotted to represent the assumed total freshwater discharge into the head of the estuary. For small values of R (less than $6 \times 10^6\ m^3/day$), it was not possible to estimate the value of F from the salinity profiles. The graph shows that for the discharge values normally expected for this estuary, the flushing time ranges from about 1.5 to 2 days.

This flushing time of 1.5 to 2 days represents the very special case of a pollutant having characteristics virtually identical to those of the incoming fresh water. For the case of a pollutant whose density lies between that of fresh water and salt water and which becomes mixed with the river waters, the time needed to reduce the concentration of the pollutant to a negligible value with respect to the total river volume is estimated to be approximately 15 days.[17]

CONCLUSIONS AND RECOMMENDATIONS

Observations of electrical conductivity, temperature, and salinity in the Thames River have been used to provide a description of the salinity distribution in this estuary. Longitudinal profiles of salinity versus depth show that the river is basically a two-layer flow-type estuary, taking on the characteristics of a salt wedge type of estuary under conditions of high freshwater discharge. The freshwater discharge into the estuary is usually small, and during most of the year the river is of relatively high salinity throughout its length. During periods of high stream discharge, however, the head of the salt wedge may be pushed several kilometers downriver by the freshwater flow from the major tributaries.

Salinity stratification has been plotted as a function of location along the length of the river for several values of freshwater discharge to show the effect of river

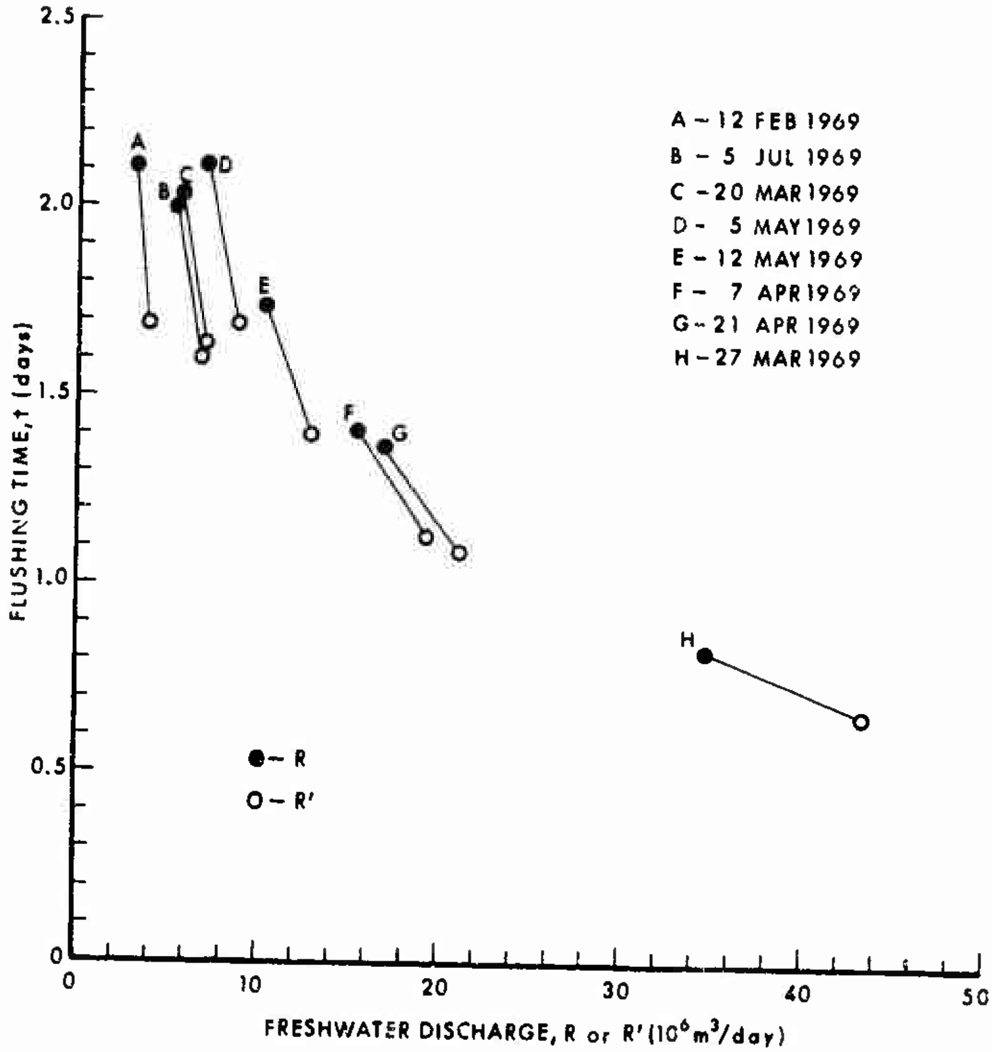

Fig. 15. Estimated Flushing Time for a Pollutant Introduced at the Head of the Thames River Estuary (Norwich Basin)

topography upon the salinity structure during the ebb and flood of the tides. The occurrence of some degree of turbulent mixing is indicated by the data in those regions where sharp changes occur in the cross-sectional area of the river.

The flushing time for a very special case was estimated from the salinity profiles to range from about 1.5 to 2 days, depending upon the amount of fresh water discharged into the river. This quantity may be used to estimate the time required to clear the estuary of a pollutant that has been introduced at the head of the estuary, provided that the pollutant density is virtually identical to that of the fresh water. The flushing time for denser pollutants that have become mixed in with the river waters may be on the order of 15 days.

The visual impressions of the salinity profiles and the salinity stratification graphs have served to provide an introduction to the fresh/salt structure of this river. However, even though these profiles and graphs have numbers associated with them, they might almost be considered more impressionistic and qualitative than quantitative, for the river is dynamic and its characteristics are constantly changing even as one proceeds from one measurement site to the next. This is not to say that the measured values are not valid, but rather that for proper interpretation of the observed variations in the salinity distribution much more supporting information will be needed. It is important that meteorological data such as wind speed and direction, air temperature, and upland rainfall data be obtained for the immediate area.

The effects of the wind in piling up or blowing away the surface waters at various locations along the river and in causing abnormal tidal conditions would appear to be a necessary consideration. Data on the river current velocity profile at each measurement site will be of importance in determining the dynamics of the variations in the fresh/salt water structure. Transverse (cross-river) measurements of conductivity, temperature, and salinity are needed to provide information on the effects of eddy currents in the broad, shallow areas adjoining the navigation channel.

The measurements reported here were made for the specific purpose of determining the fresh/salt water structure of the Thames River in support of a particular laboratory investigation. No provisions were made to obtain auxiliary information such as the instantaneous current velocity or the tide height at each site at the time of measurement. Future work will include provisions for simultaneously obtaining data on as many of the associated parameters as found necessary.

Related measurements will be made as time permits. For example, a series of current velocity measurements is to be made shortly. Three Braincon ducted-impeller current meters, mounted at intervals along a staff, will be immersed vertically in the stream to obtain current velocity profiles at selected sites along the river. Measurements will be made first at sites having relatively narrow cross sections (Sites 6, 10, and 14). Subsequent measurements may then be made in the shallow areas for studies of eddy currents.

For the planning of future measurements, it is suggested that the river may be divided into several major sections according to the effects of the topography of the river bed upon the salinity distribution and the salinity stratification characteristics. Such a division may allow a more meaningful description of the estuary for some applications than would a general description of the river as a whole. An arbitrary division of the Thames River is shown on the map at the top of Fig. 14, where the segments have been designated as A, B, C, D, and E (See also Table 3). These quite natural divisions are bounded as follows:

A — New London Harbor — bounded at the mouth by a line connecting Eastern Point, Groton, with the New London Ledge Light and at its north end by the railroad and highway bridges.

B — Coast Guard-Submarine Base Area — bounded at its lower end by the railroad and highway bridges and at its upper end by the top of the widely dredged turning basin near Smith Cove.

C — Harvard-Yale Boathouse Area — bounded at its lower end by the beginning of the narrow channel near Smith Cove and at its upper end by the constriction of the river at the location of the overhead power cable crossing just above Horton Cove.

D — Massapeag Shallows Area — bounded at its lower end by the constriction of the river at the overhead power cable crossing and at its upper end by the Mohegan-Pequot Bridge. The river is spread out over a relatively large expanse of shallows to one or the other side of the channel.

E — Long Rock Dike Area — bounded at its lower end by the Mohegan-Pequot Bridge, and at its upper end by the Norwich tidal basin. This area features several stretches of rock dikes along the sides of the navigation channel.

For some applications in acoustics and electromagnetics, questions arise concerning prediction of characteristics of estuaries in general. How can one predict, for example, the expected thickness of the freshwater layer and the thickness of the transition layer between the fresh and salt waters at any desired location along an

estuary, given the upland freshwater discharge, the tidal and current information, and the meteorological data for that area? By what parameters may a river or estuary be characterized in order that a minimum of sampling is required for an instantaneous readout of salinity distribution? It would appear that a judicious choice of the parameters to be measured could lead to a rapid hit-and-run technique that would require only that the sampling be done during a specific set of conditions, such as at a certain tide phase immediately following a significant rainfall.

The experience to be gained in studying the Thames River, which is right at our own doorstep, will add much to our capabilities for future studies of other estuarine areas.

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Appendix A

GRAPHS OF CONDUCTIVITY, TEMPERATURE, AND SALINITY VERSUS DEPTH

The following 28 sets of graphs show the profiles of conductivity, temperature, and salinity values as a function of depth at each of the measurement sites on 26 different days. The conductivity and ~~temperature~~ Salinity scales are the same (0 to 40 units) for all the graphs. However, it should be noted that although the temperature scales are all eight units wide, the scale limits have been shifted as necessary to accommodate seasonal changes.

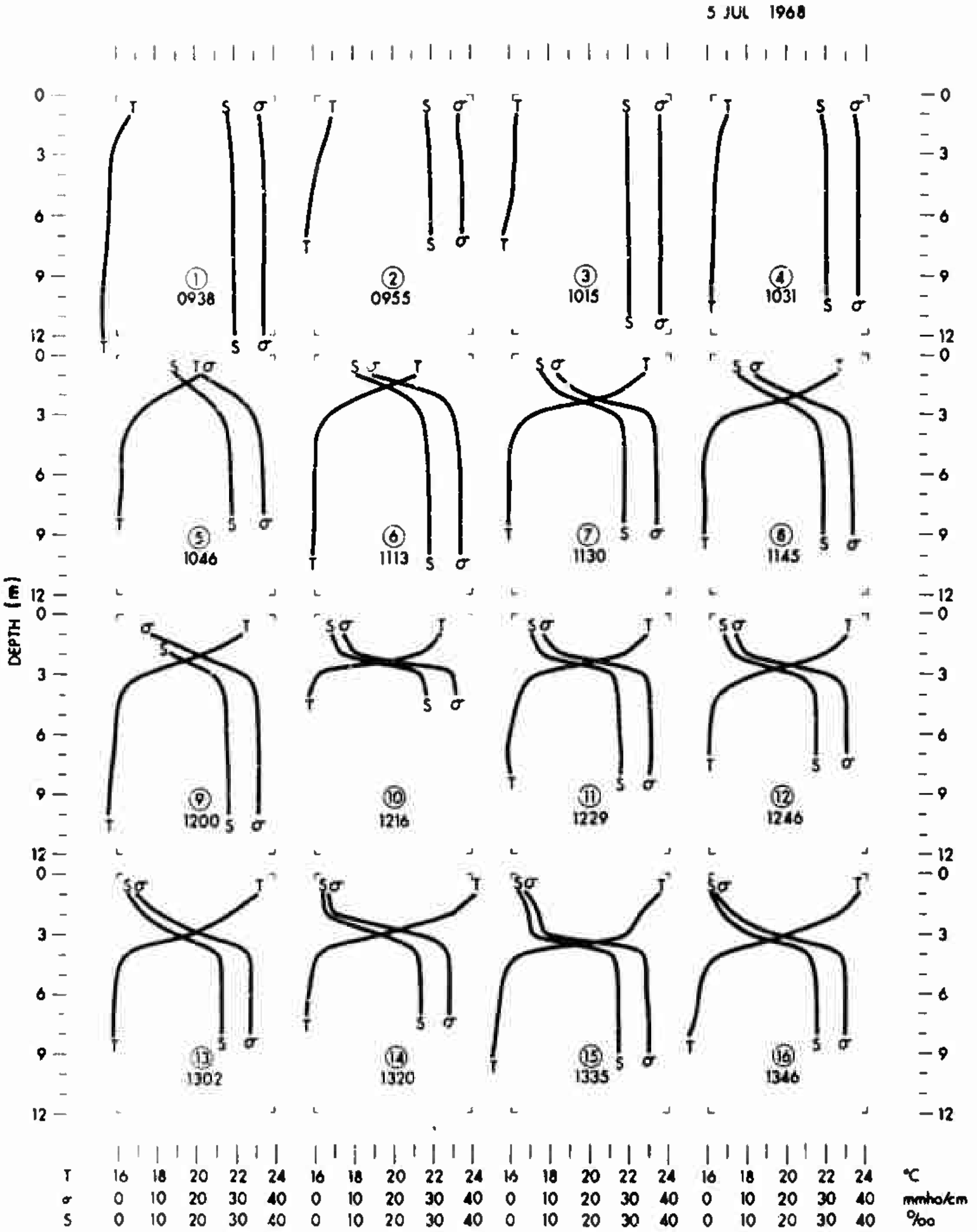


Fig. A-1. Conductivity, Temperature, and Salinity Profiles for 5 July 1968

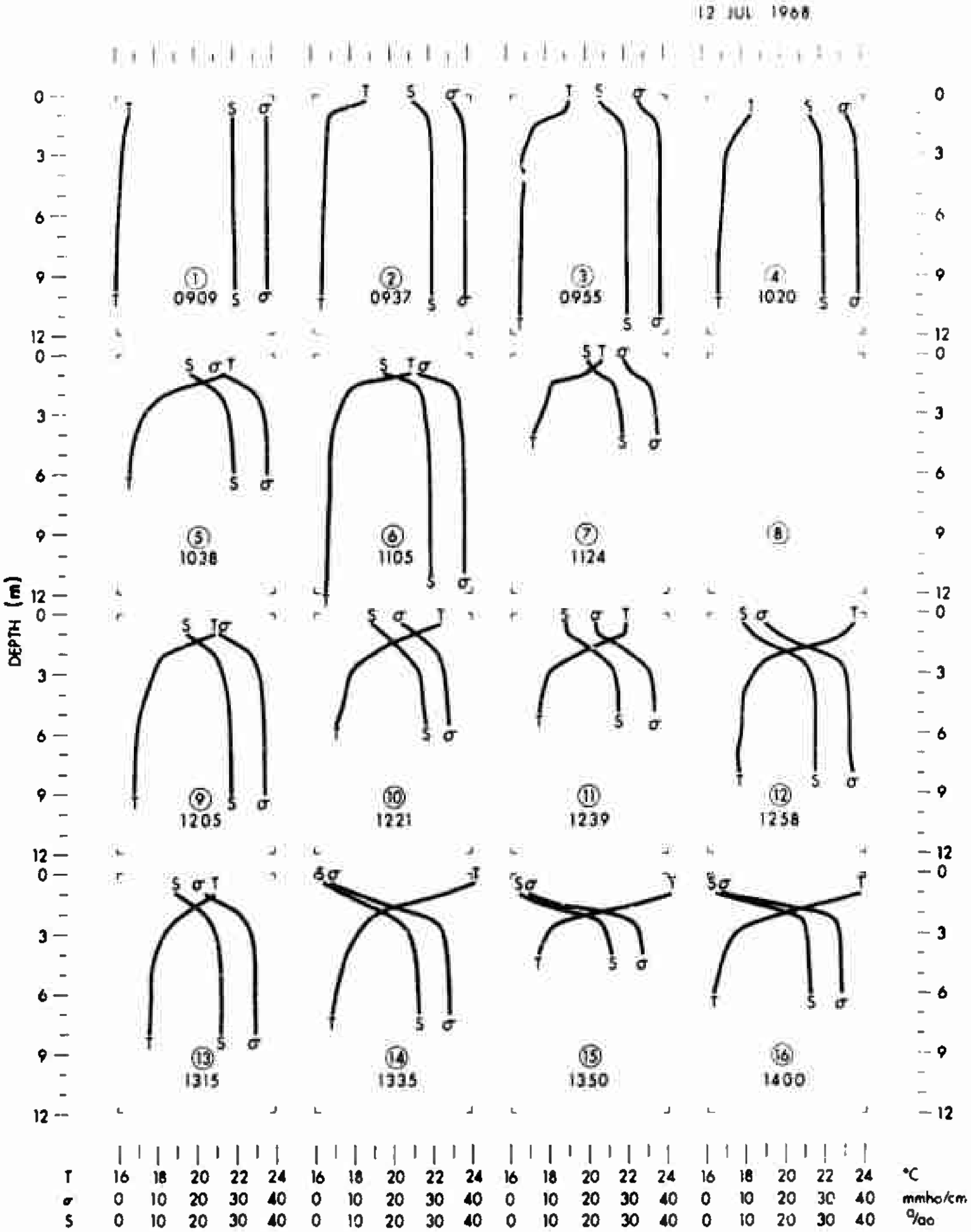


Fig. A-2. Conductivity, Temperature, and Salinity Profiles for 12 July 1968

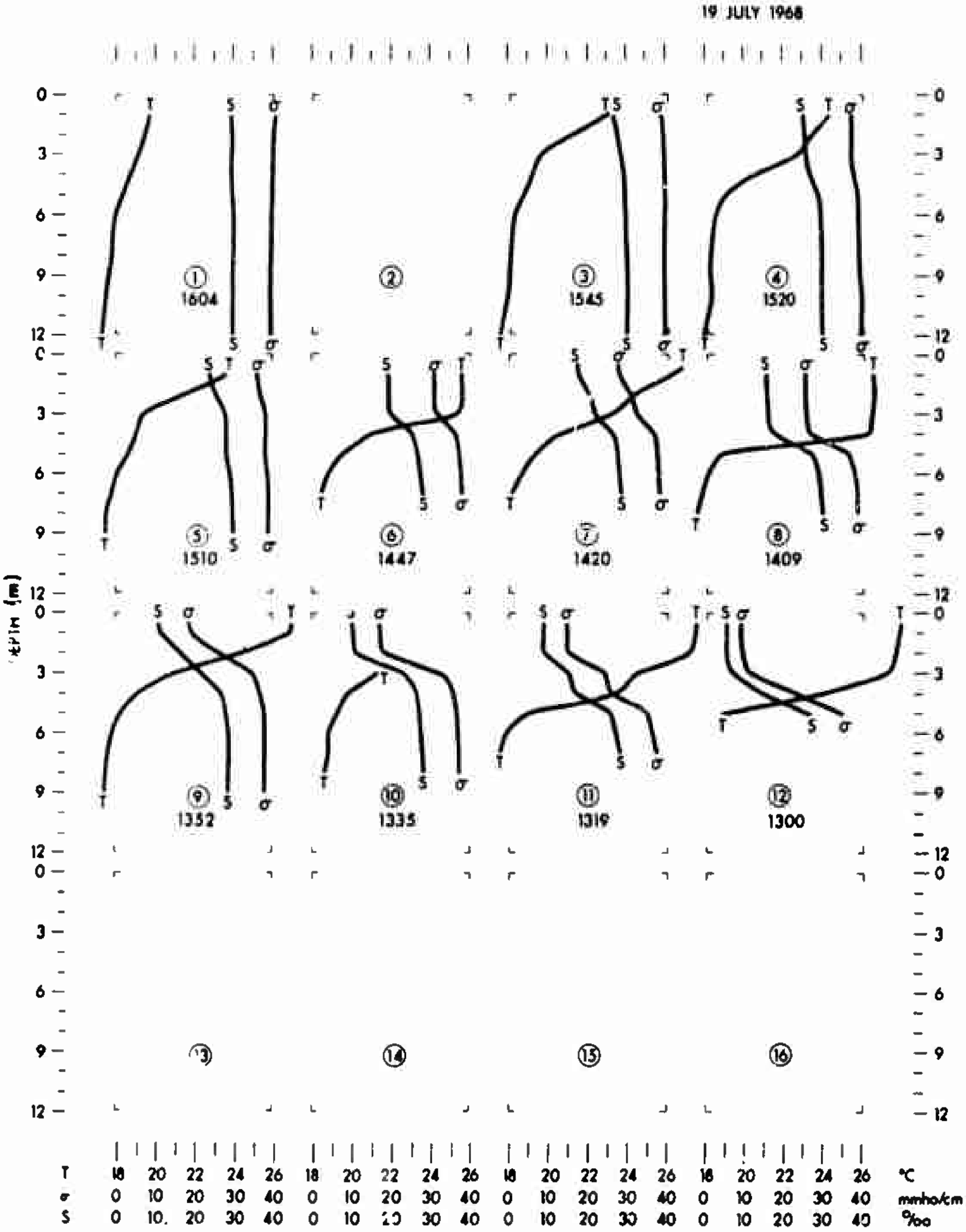


Fig. A-3. Conductivity, Temperature, and Salinity Profiles for 19 July 19

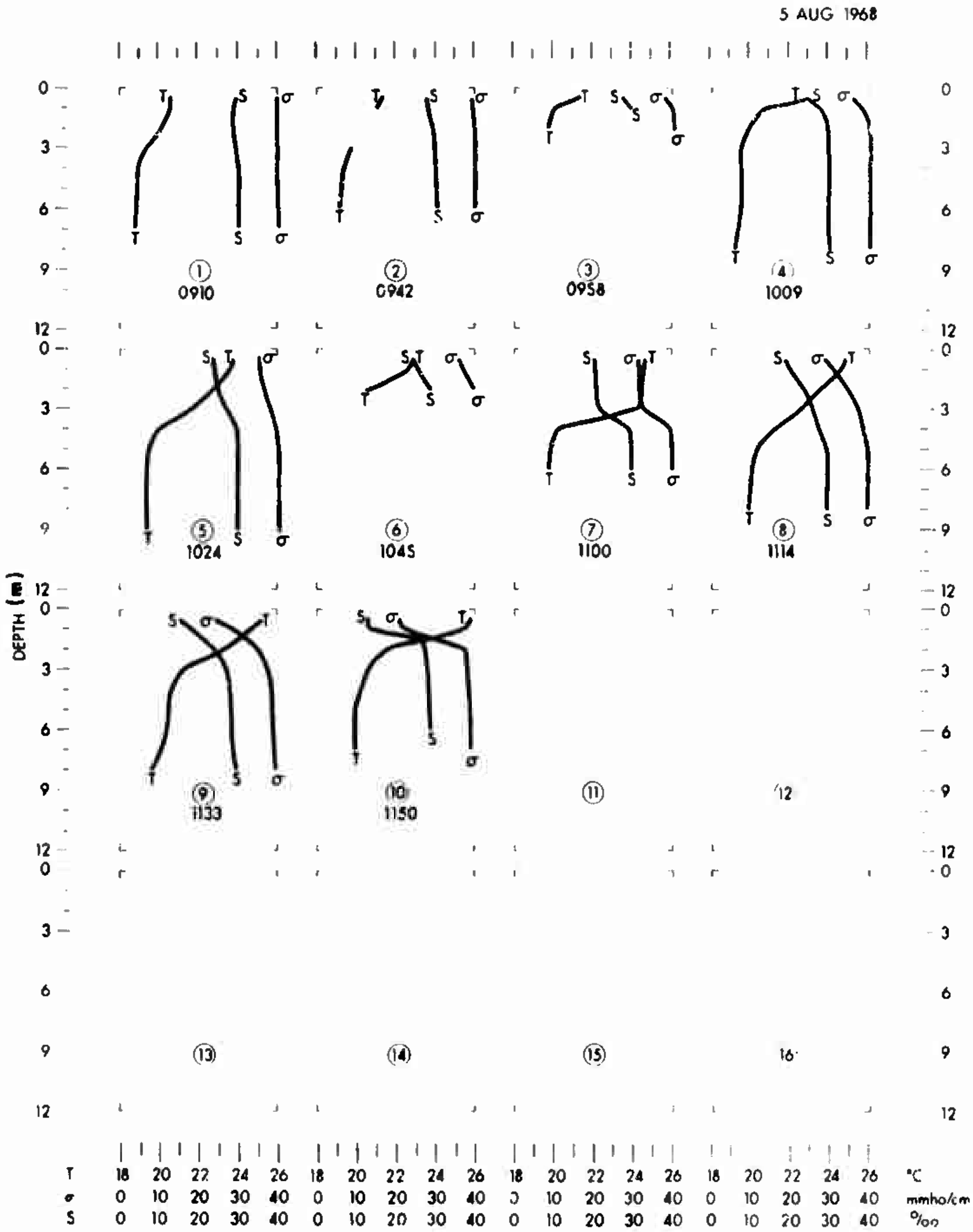


Fig. A-4. Conductivity, Temperature, and Salinity Profiles for 5 August 1968

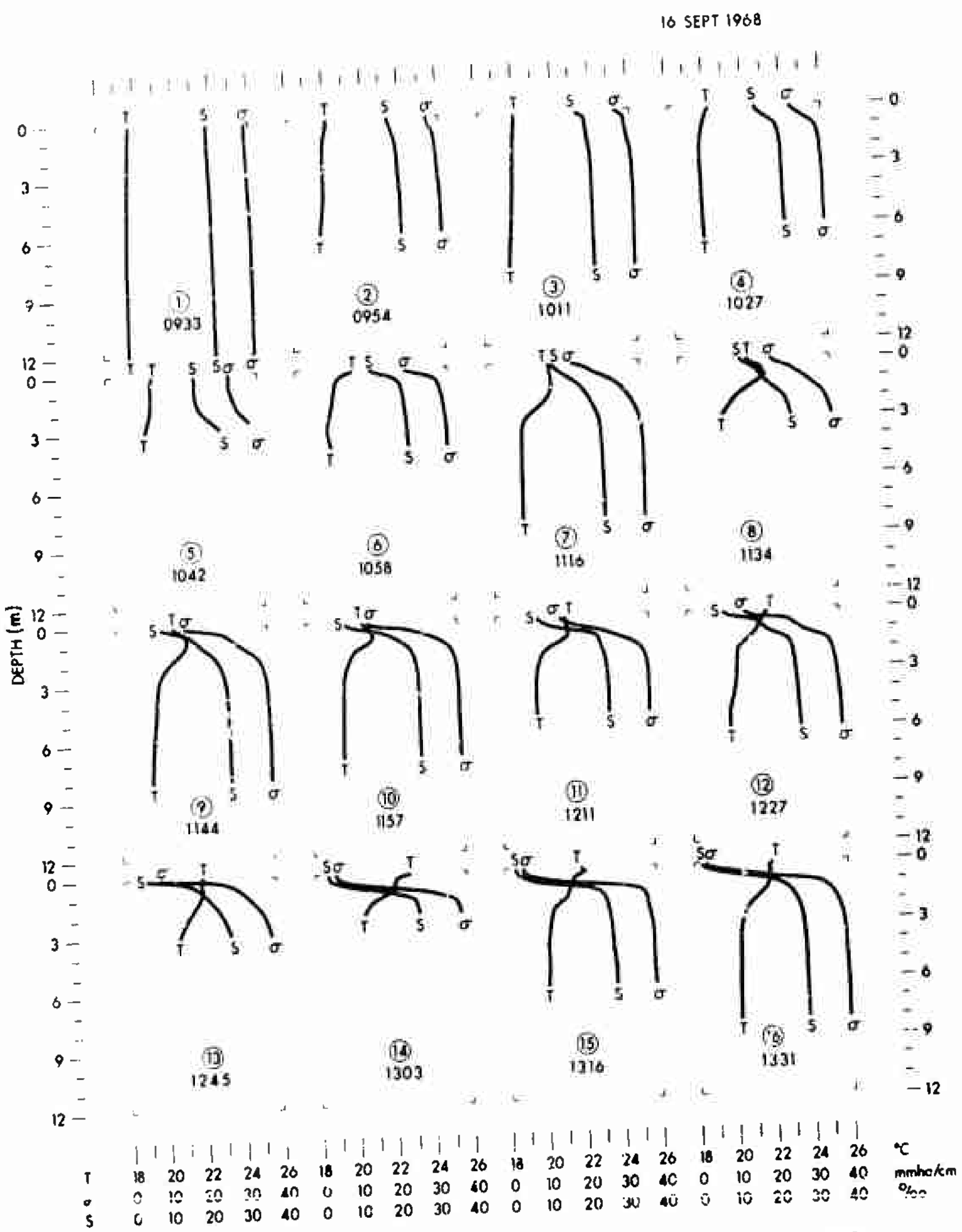


Fig. A-5. Conductivity, Temperature, and Salinity Profiles for 16 September 1968

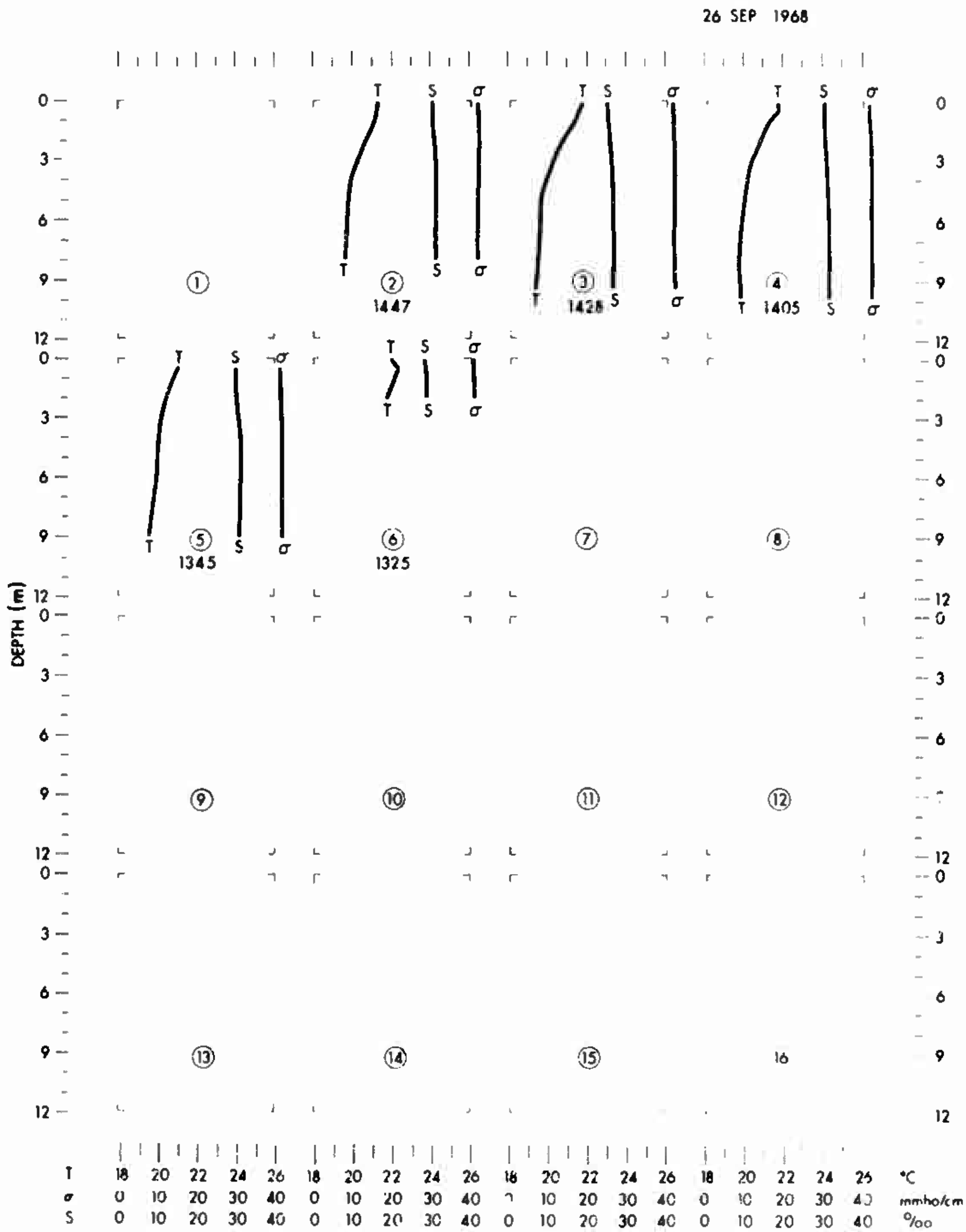


Fig. A-6 Conductivity, Temperature, and Salinity Profiles for 26 September 1968

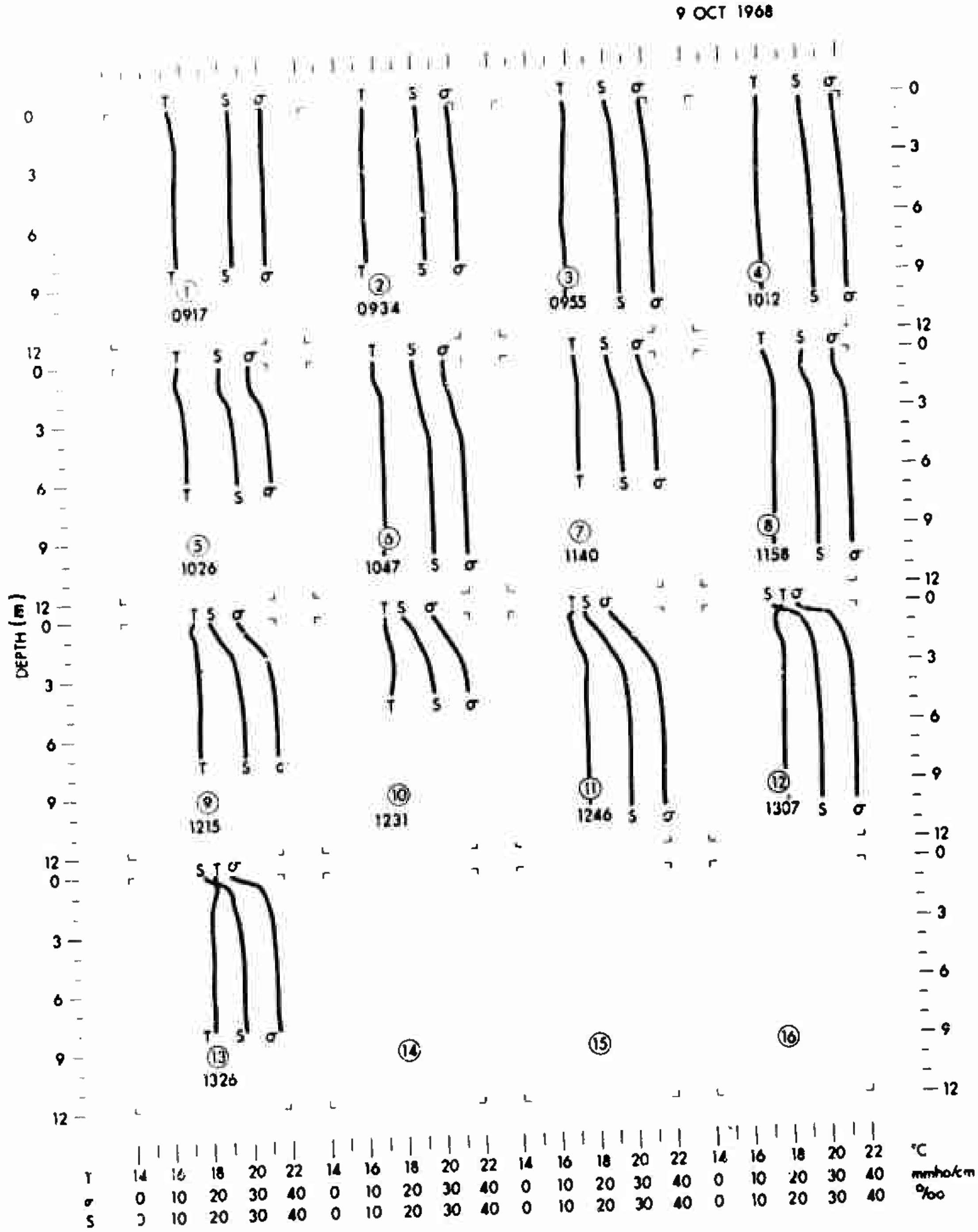


Fig. A-7. Conductivity, Temperature, and Salinity Profiles for 9 October 1968

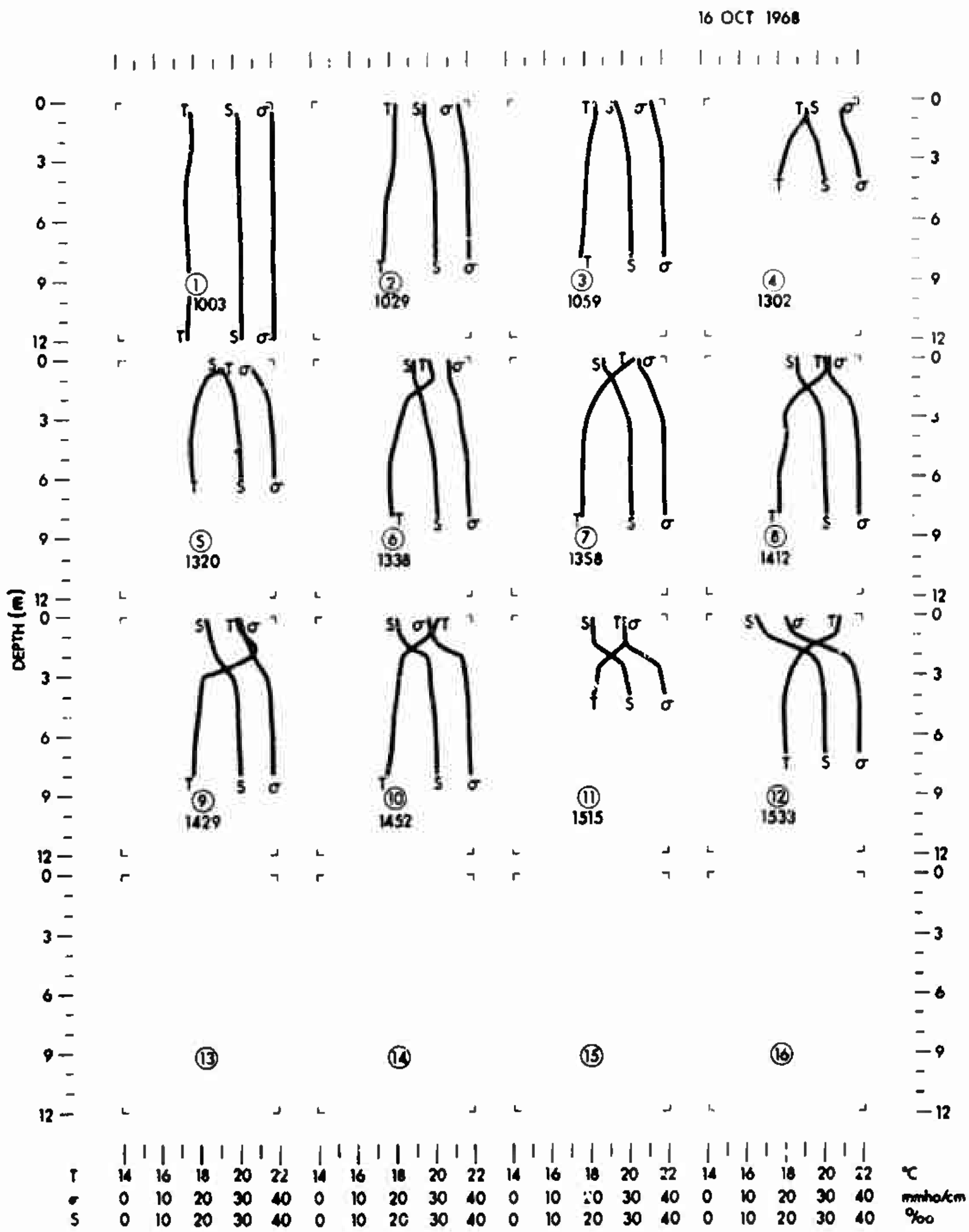


Fig. A-8. Conductivity, Temperature, and Salinity Profiles for 16 October 1968

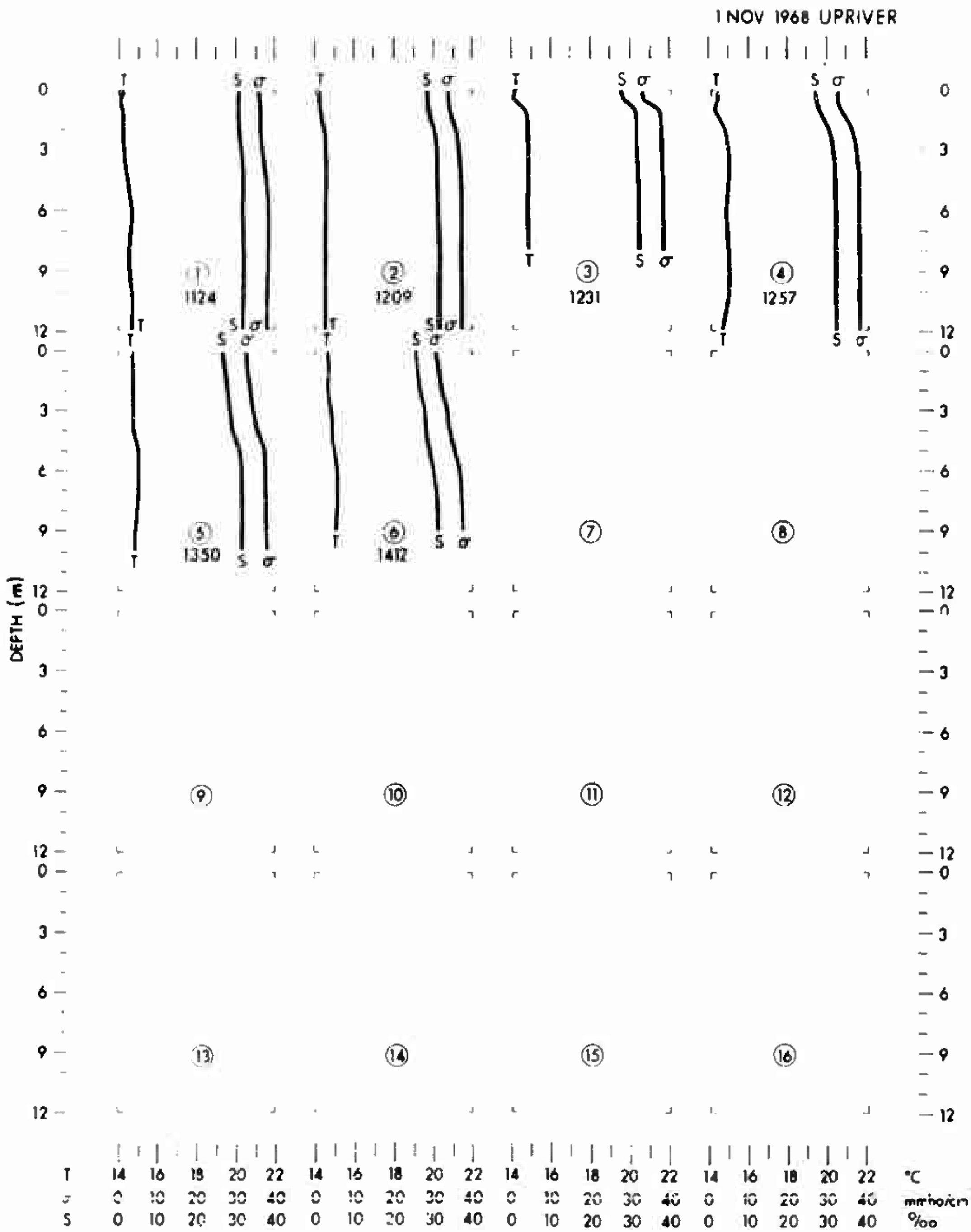


Fig. A-9. Conductivity, Temperature, and Salinity Profiles for 1 November 1968, Upriver

1 NOV 1968 DOWNRIVER

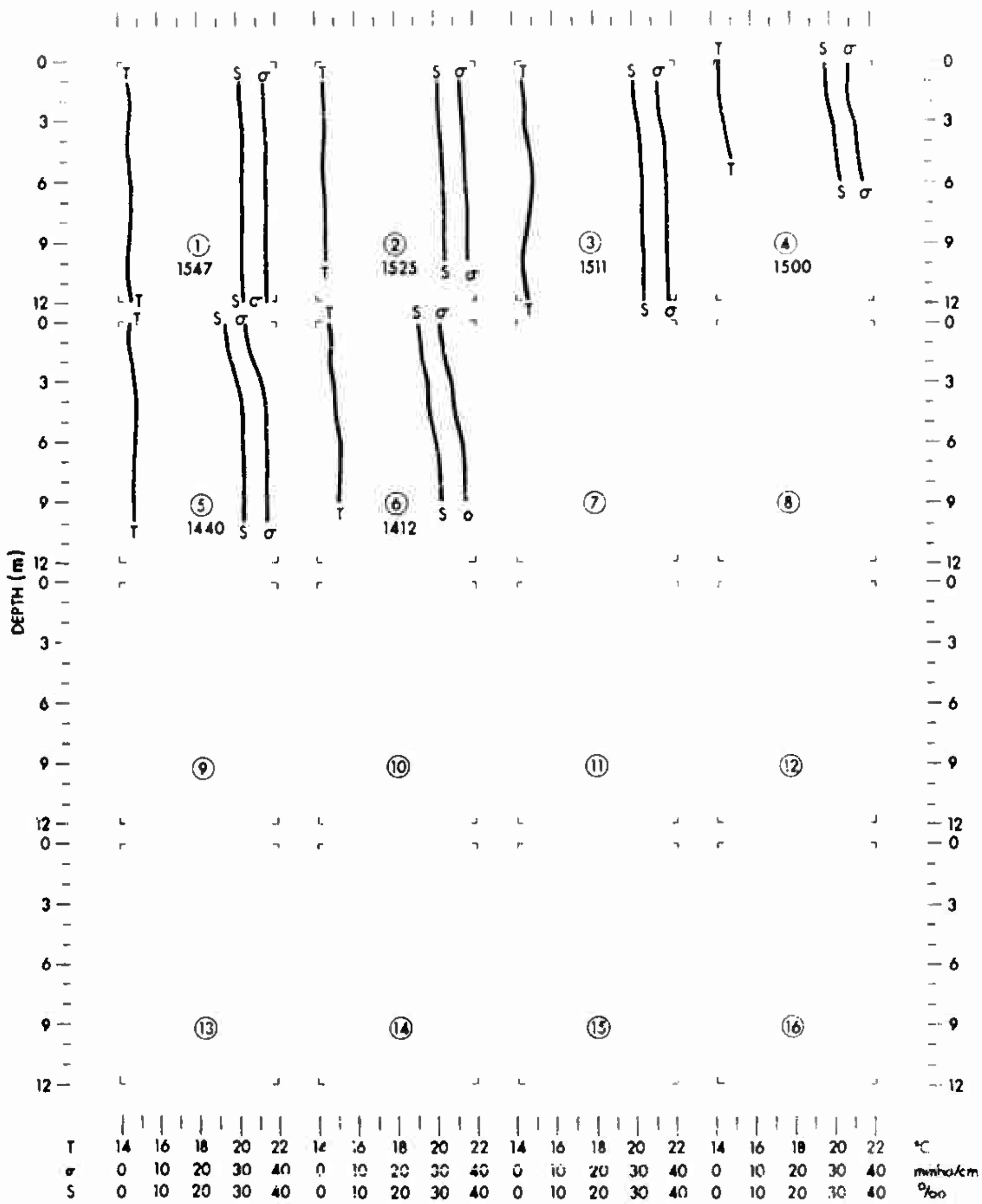


Fig. A-10. Conductivity, Temperature, and Salinity Profiles for 1 November 1968, Downriver

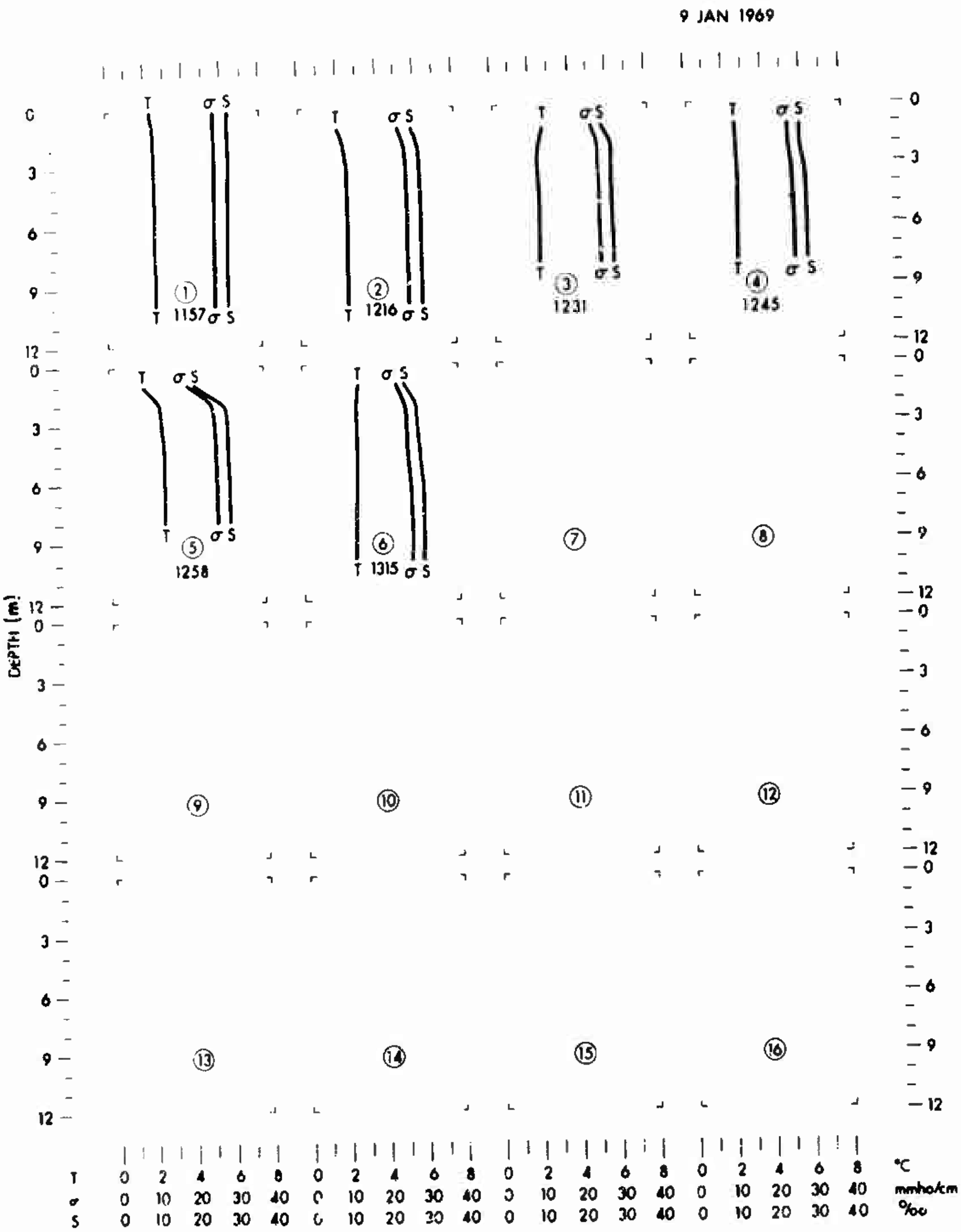


Fig. 4.11. Conductivity, Temperature, and Salinity Profiles for 9 January 1969

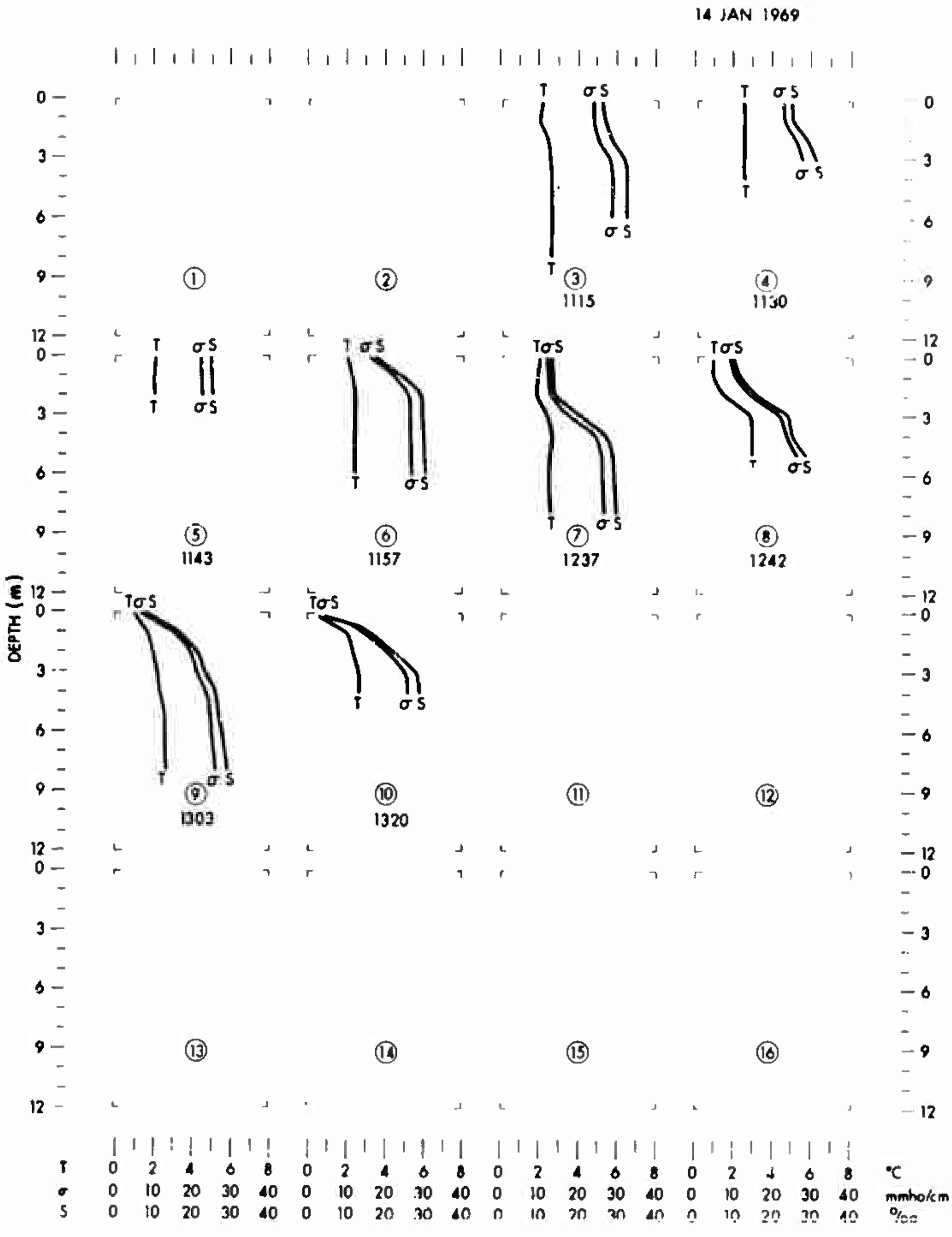


Fig. A-12. Conductivity, Temperature, and Salinity Profiles for 14 January 1969

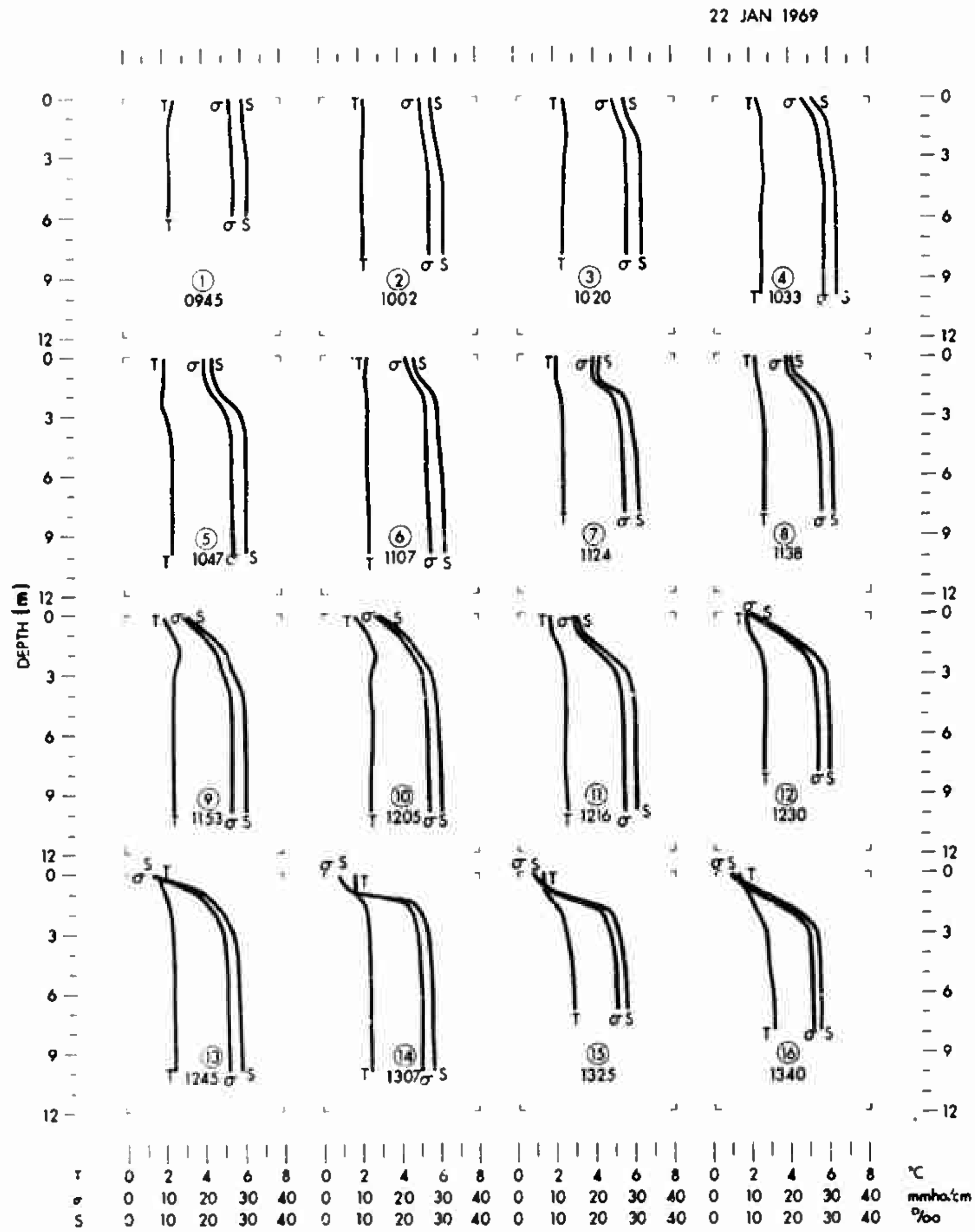


Fig. A-13. Conductivity, Temperature, and Salinity Profiles for 22 January 1969

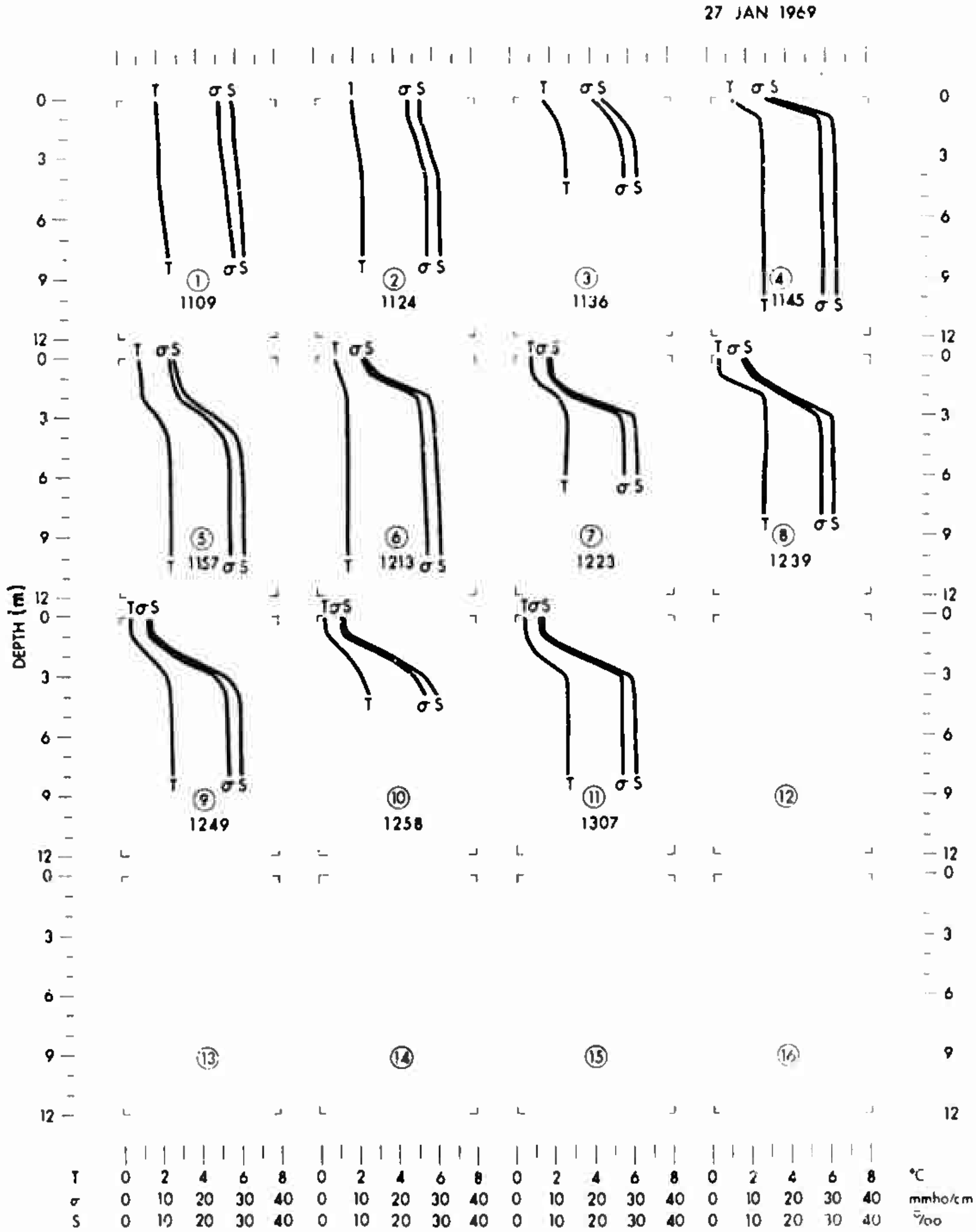


Fig. A-14. Conductivity, Temperature, and Salinity Profiles for 27 January 1969

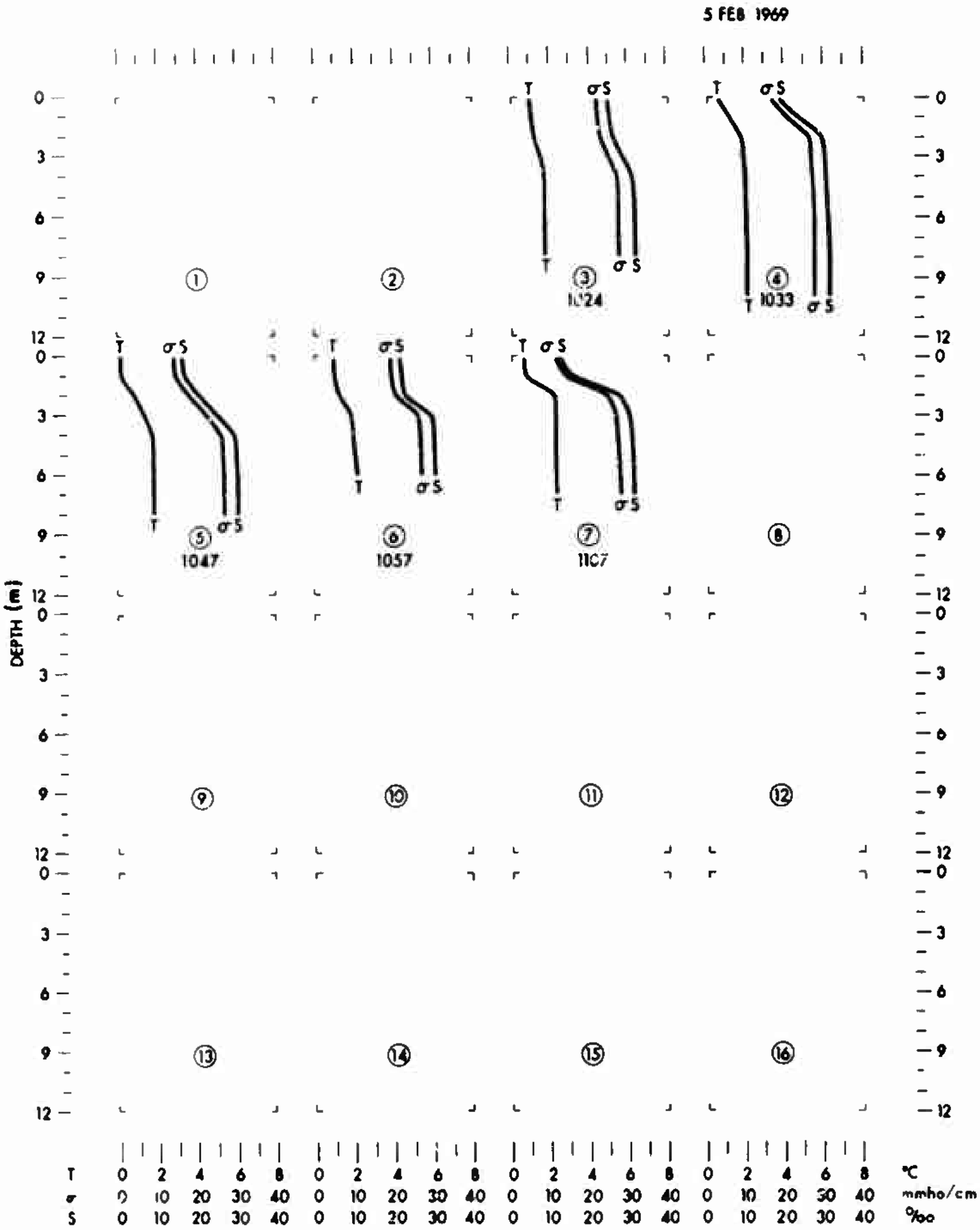


Fig. A-15. Conductivity, Temperature, and Salinity Profiles for 5 February 1969

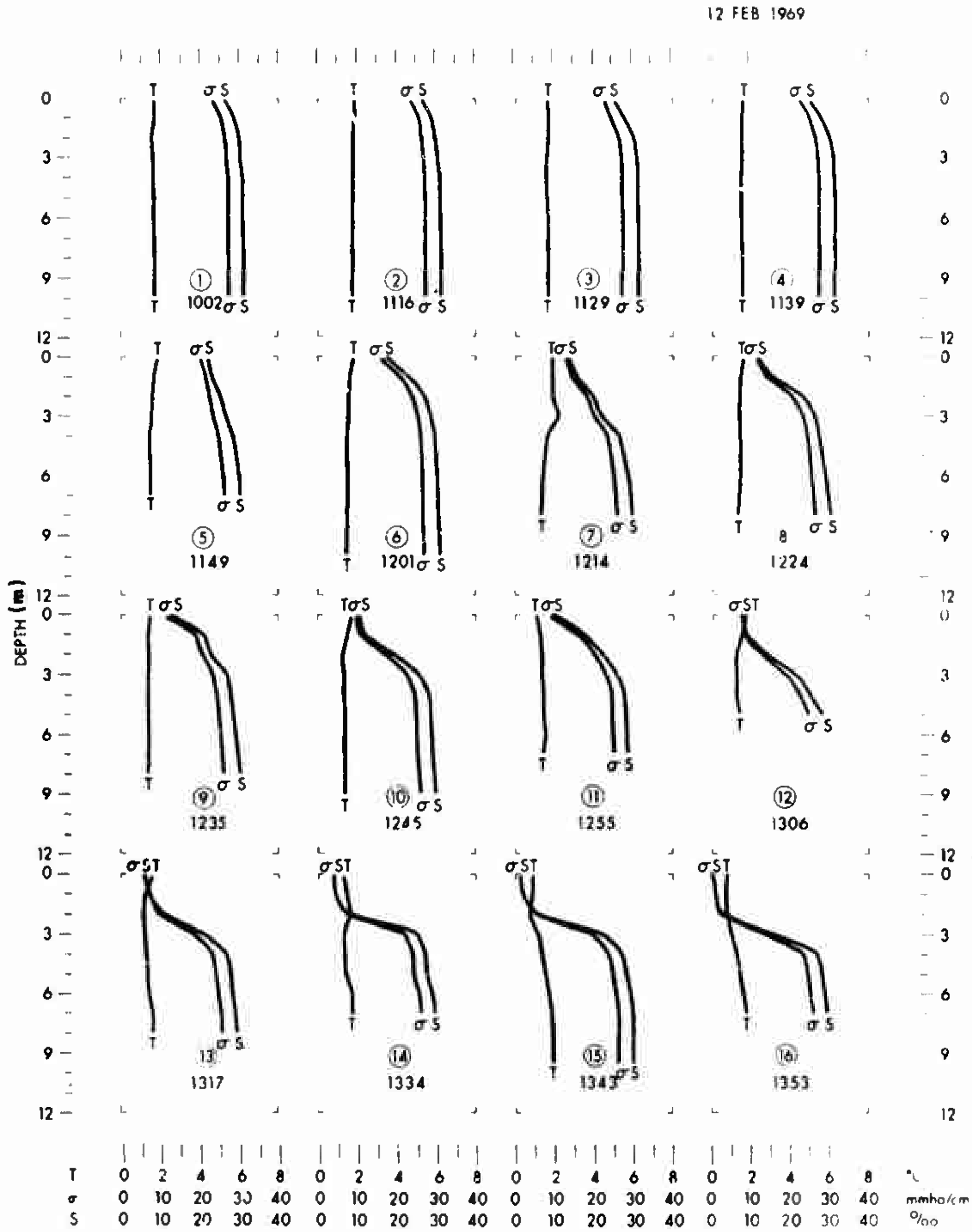


Fig. A-16. Conductivity, Temperature, and Salinity Profiles for 12 February 1969

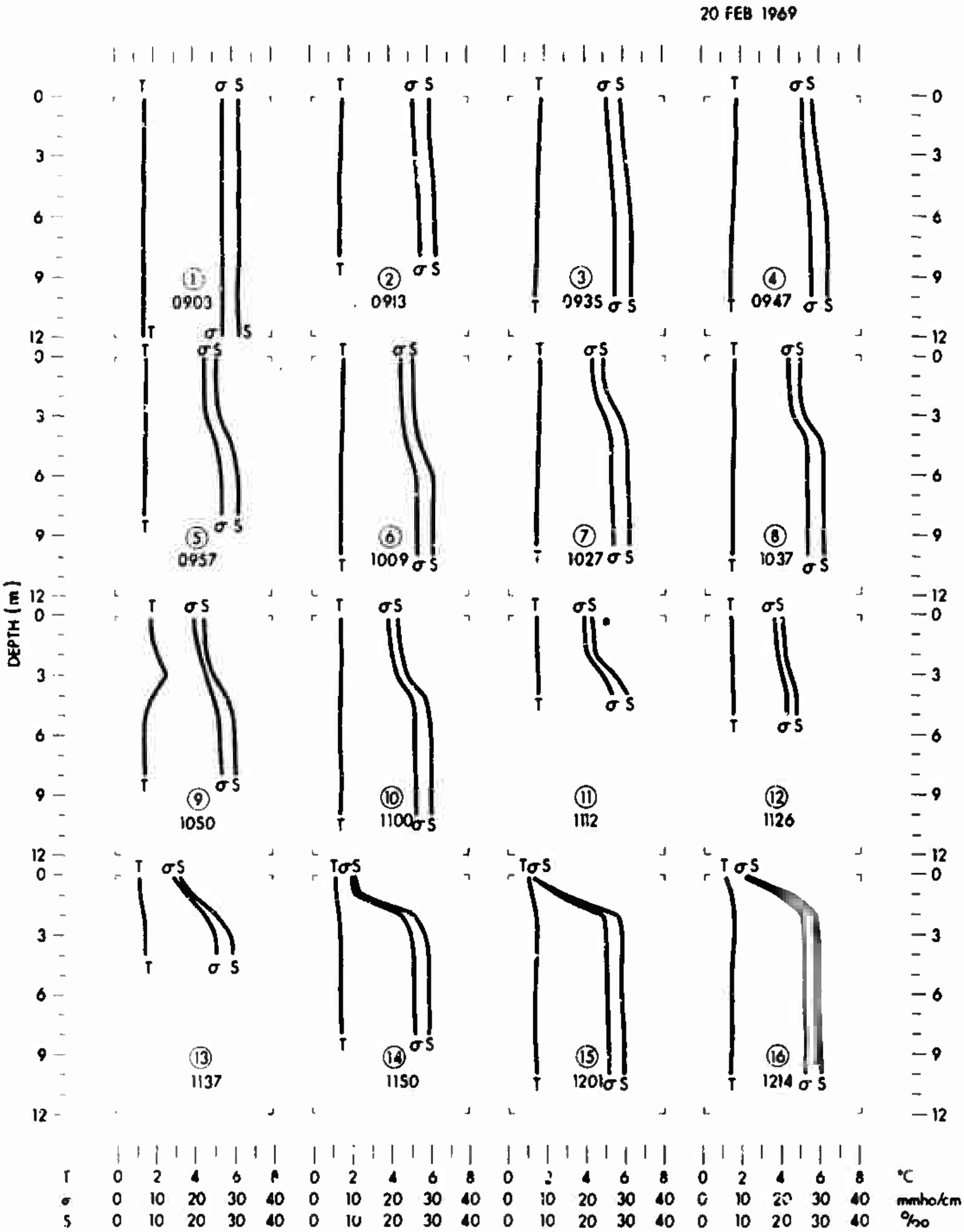


Fig. A-17. Conductivity, Temperature, and Salinity Profiles for 20 February 1969

6 MAR 1969

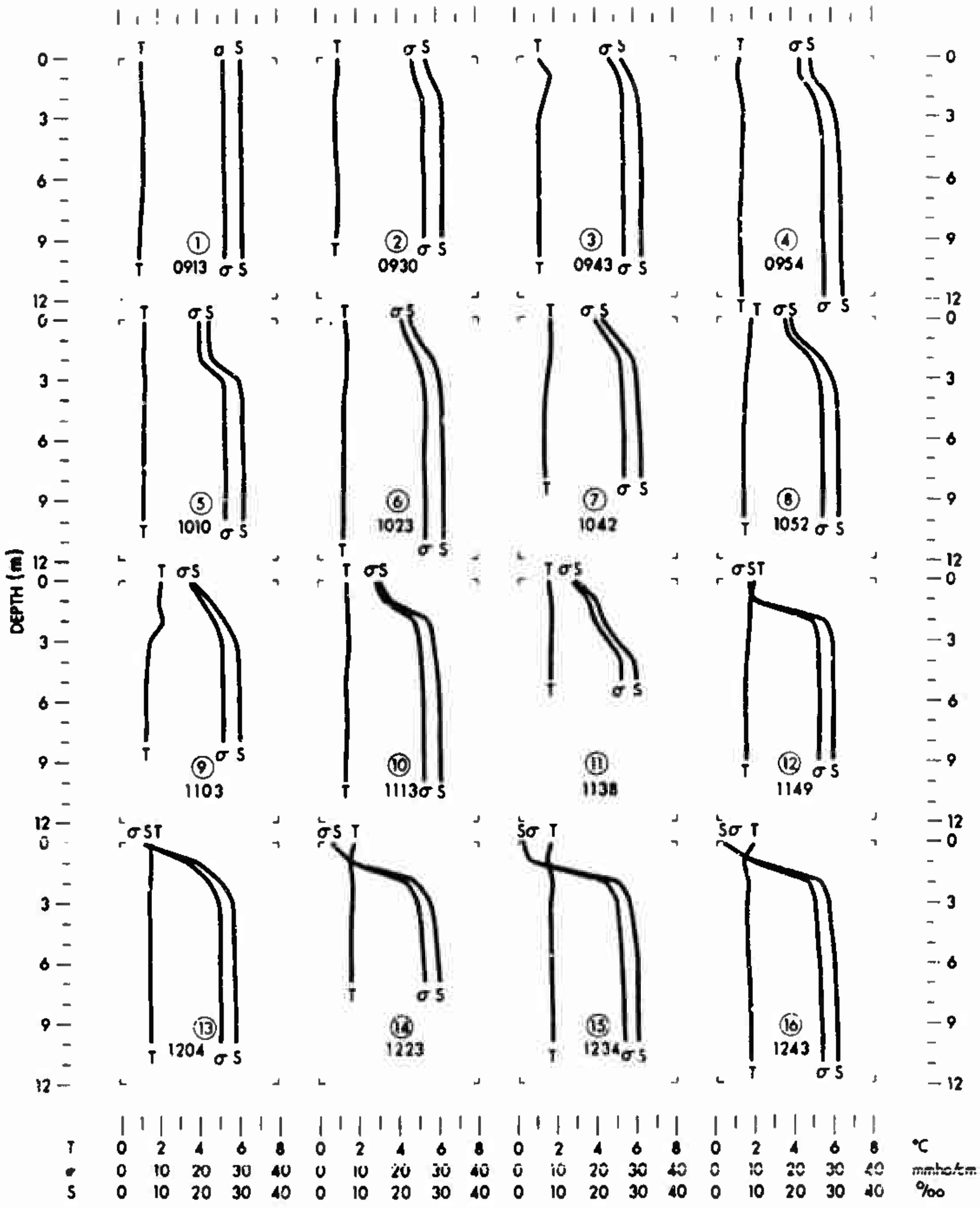


Fig. A-18. Conductivity, Temperature, and Salinity Profiles for 6 March 1969

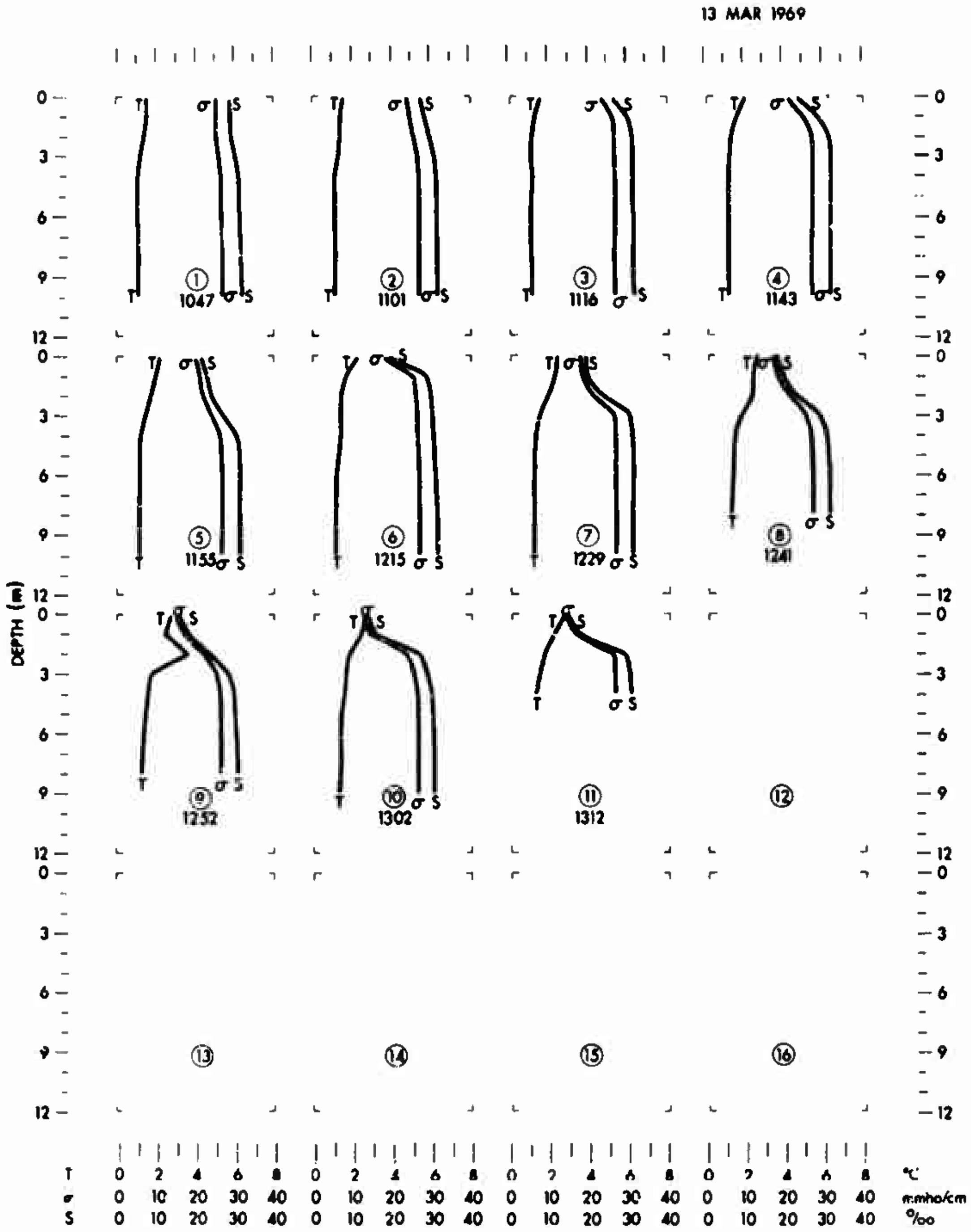


Fig. A-19. Conductivity, Temperature, and Salinity Profiles for 13 March 1969

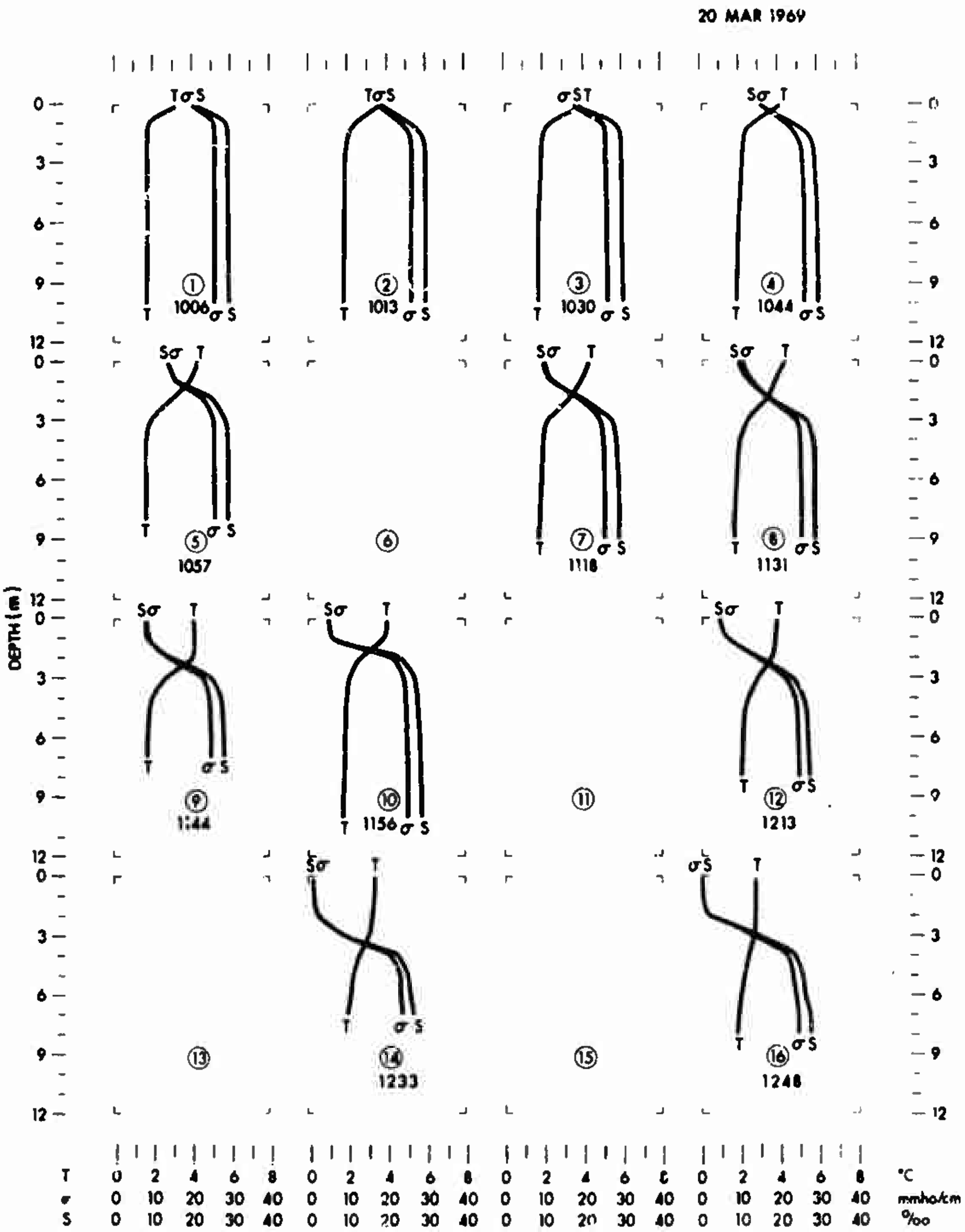


Fig. A-20. Conductivity, Temperature, and Salinity Profiles for 20 March 1969

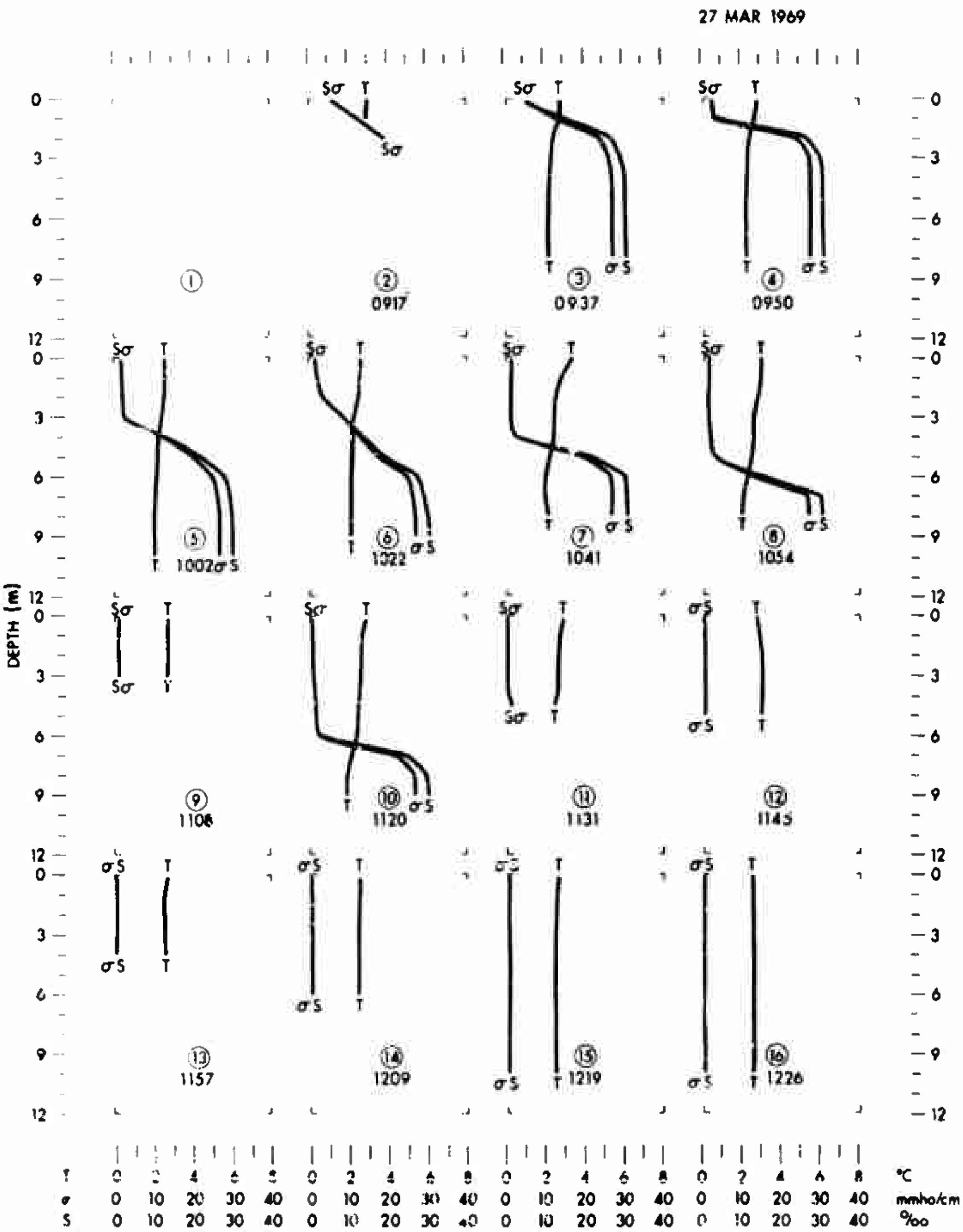


Fig. A-21. Conductivity, Temperature, and Salinity Profiles for 27 March 1969

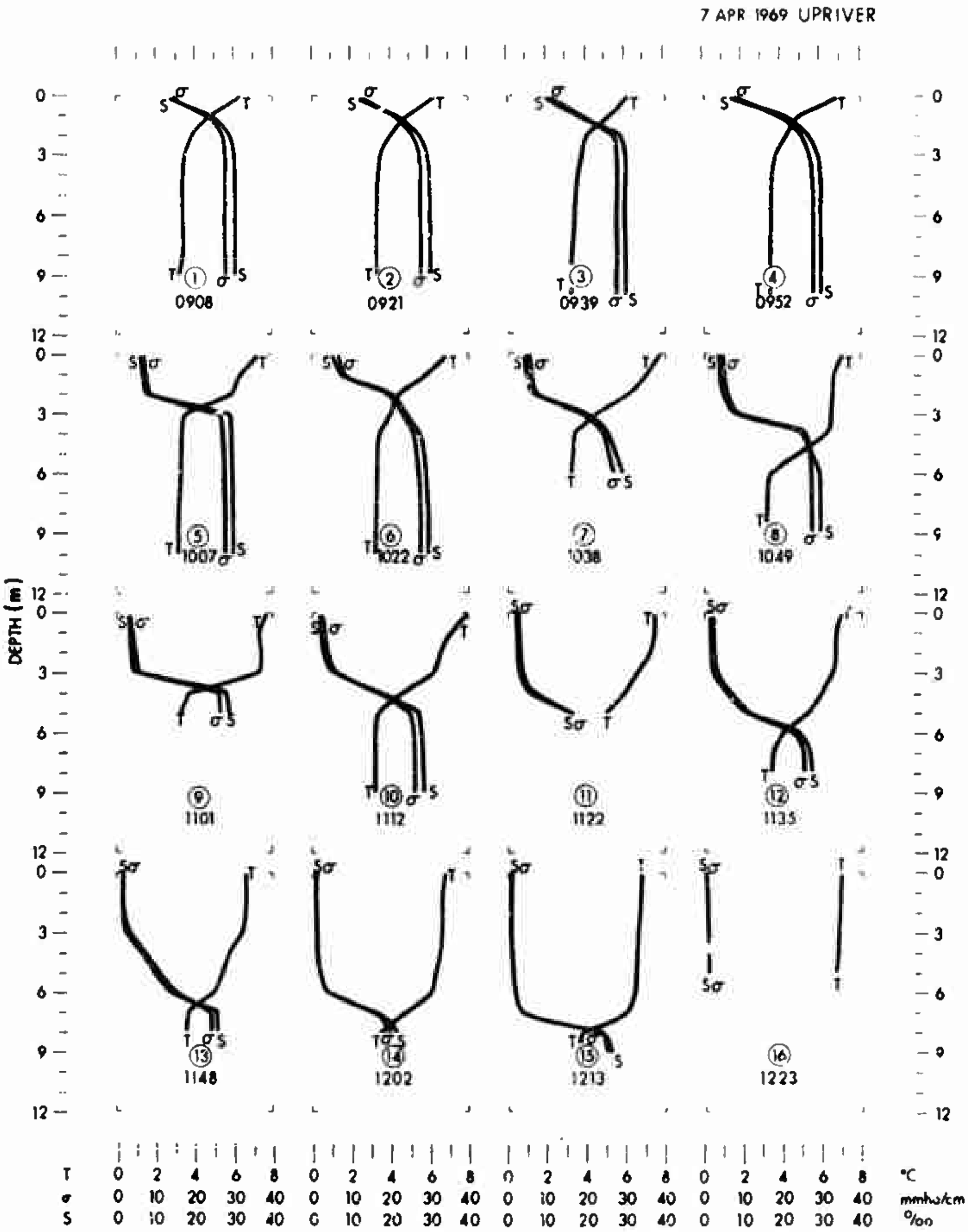


Fig. A-22. Conductivity, Temperature, and Salinity Profiles for 7 April 1969, Upriver

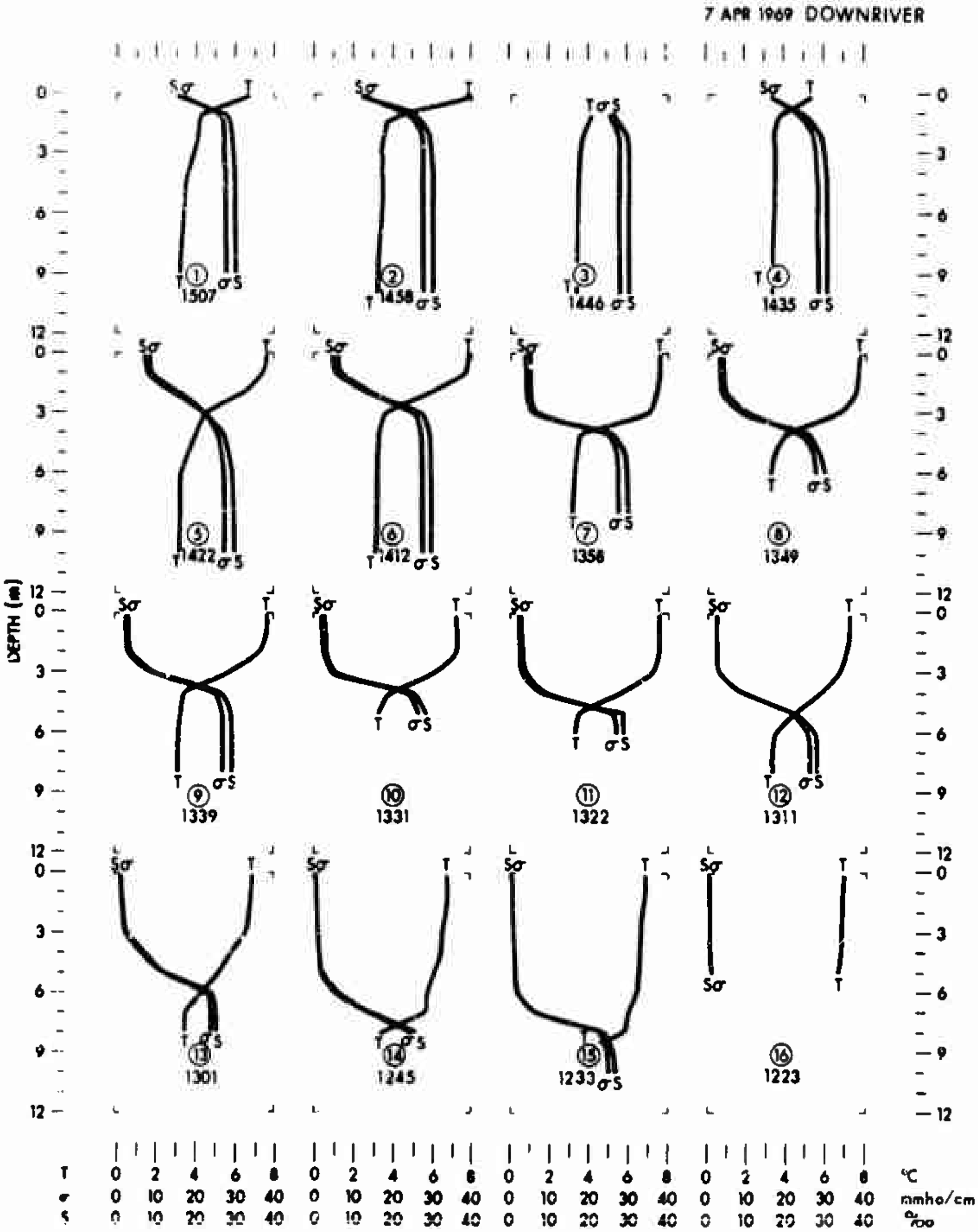


Fig. A-23. Conductivity, Temperature, and Solinity Profiles for 7 April 1969, Downriver

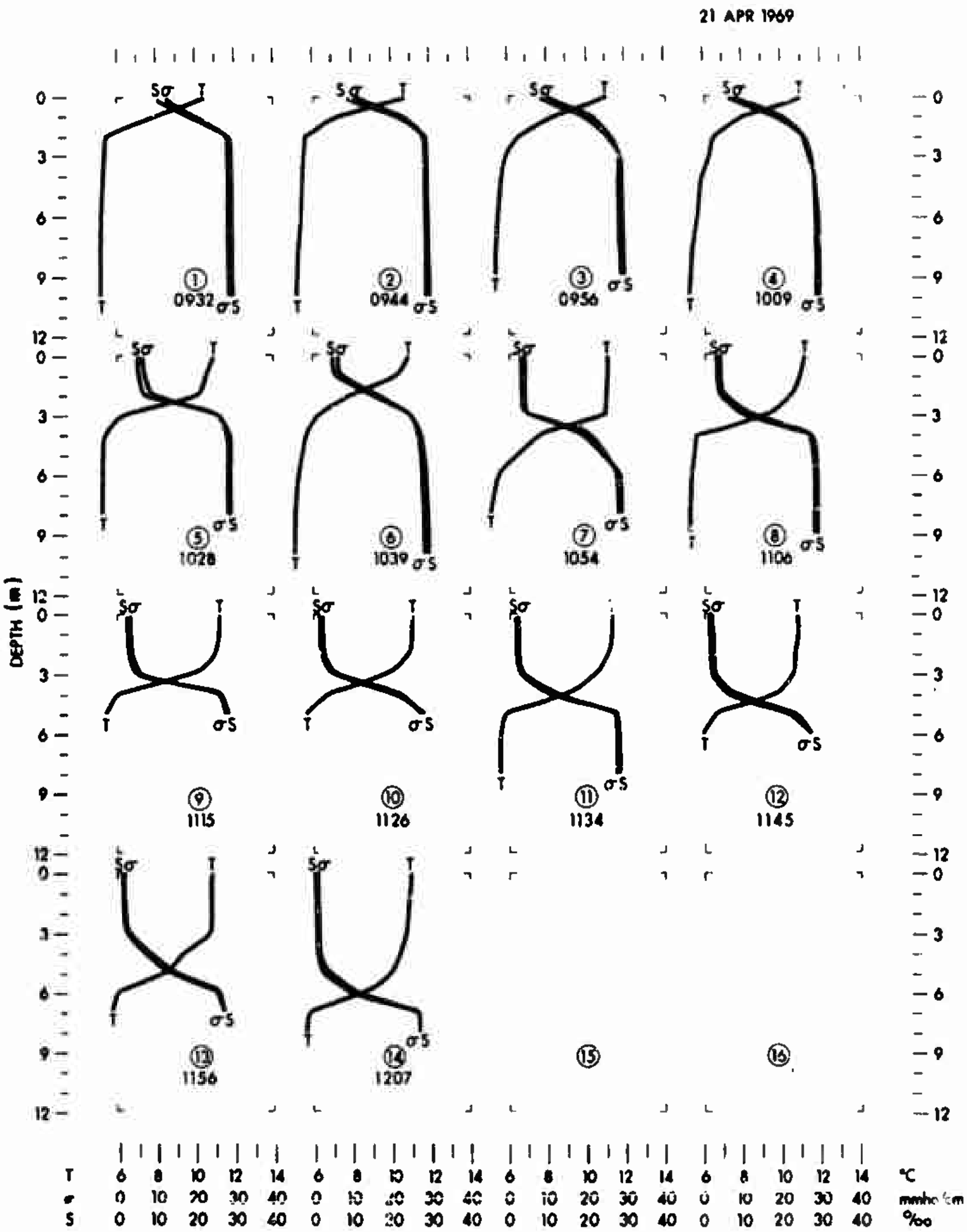


Fig. A-24. Conductivity, Temperature, and Salinity Profiles for 21 April 1969

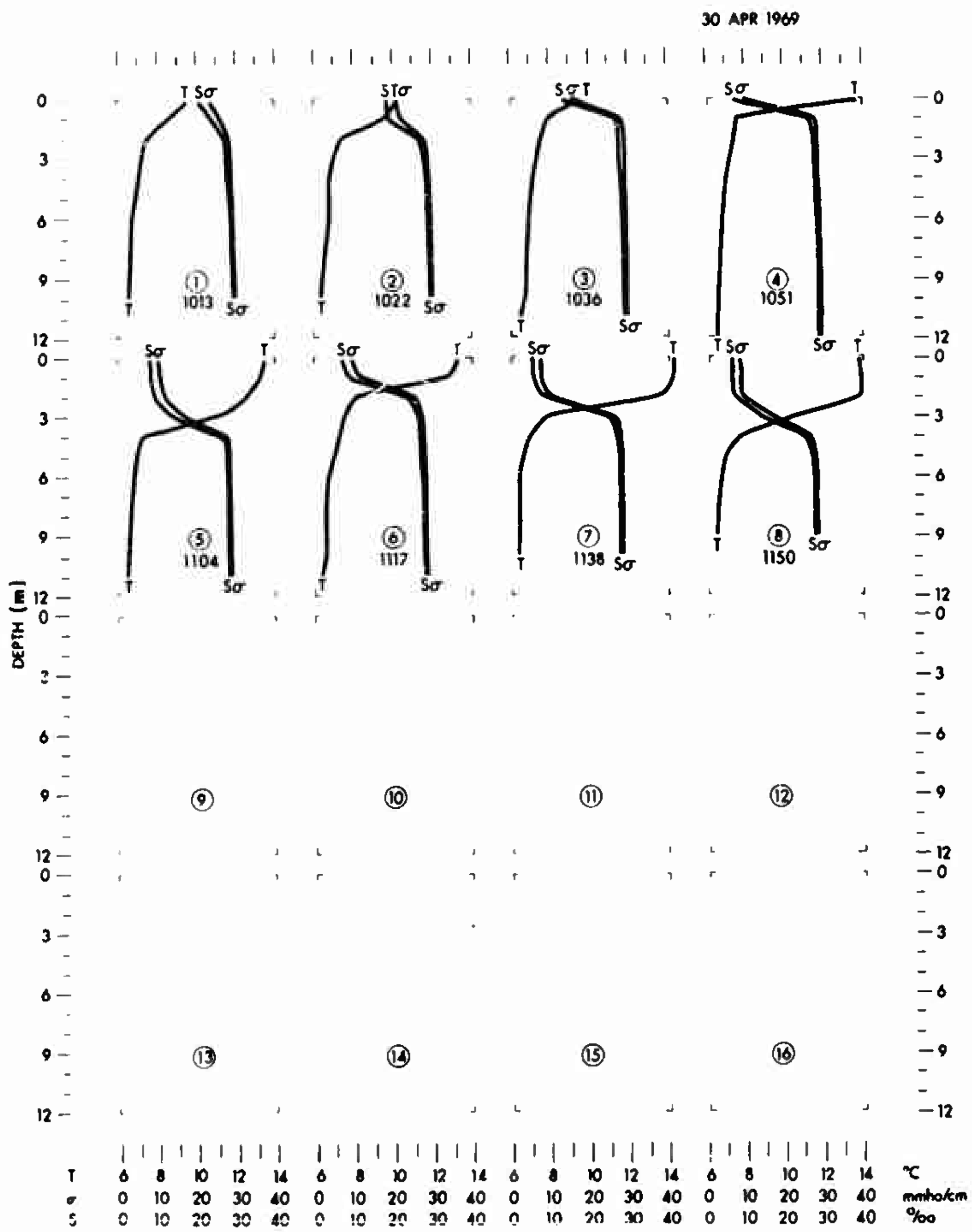


Fig. A-25. Conductivity, Temperature, and Salinity Profiles for 30 April 1969

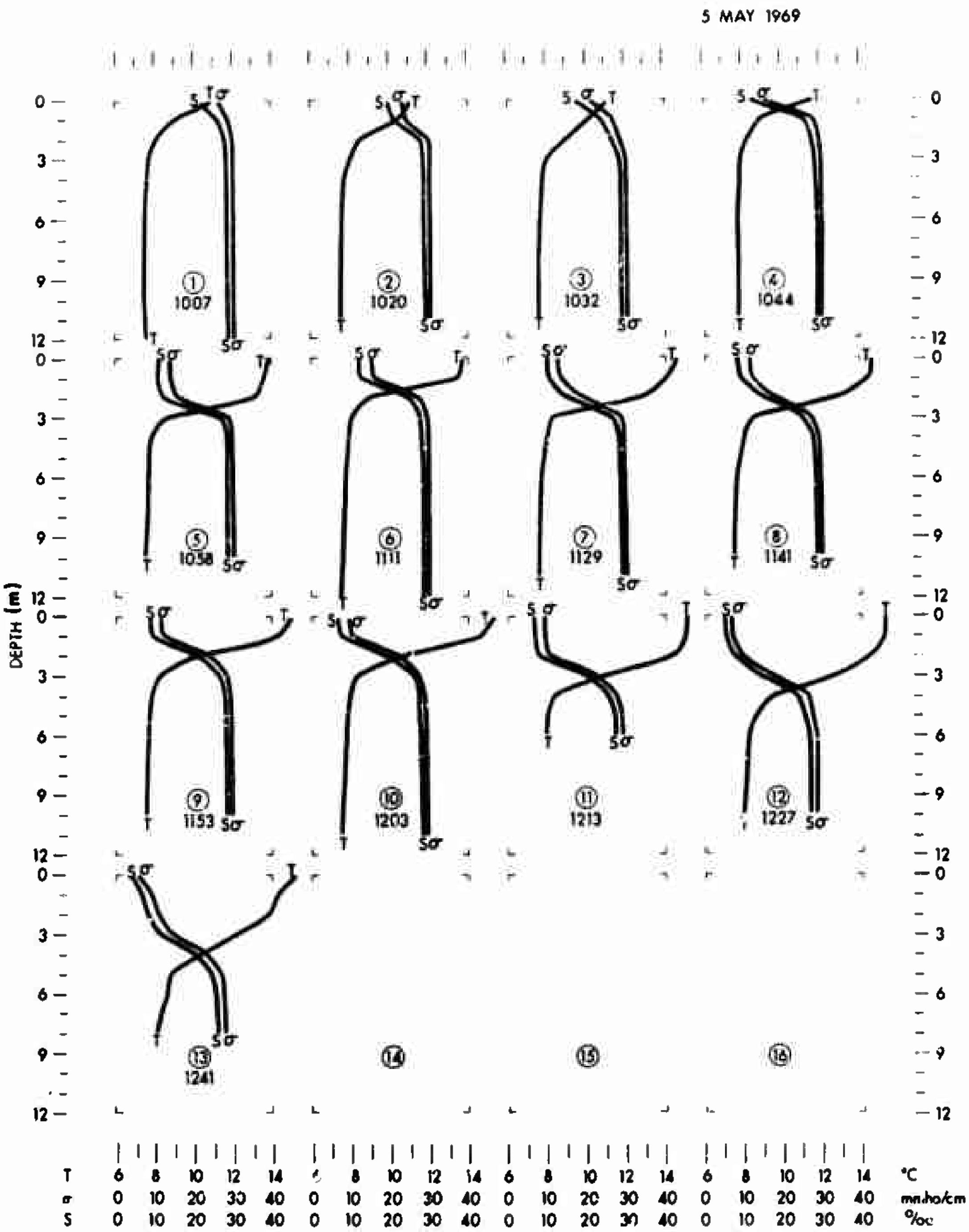


Fig. A-26. Conductivity, Temperature, and Salinity Profiles for 5 May 1969

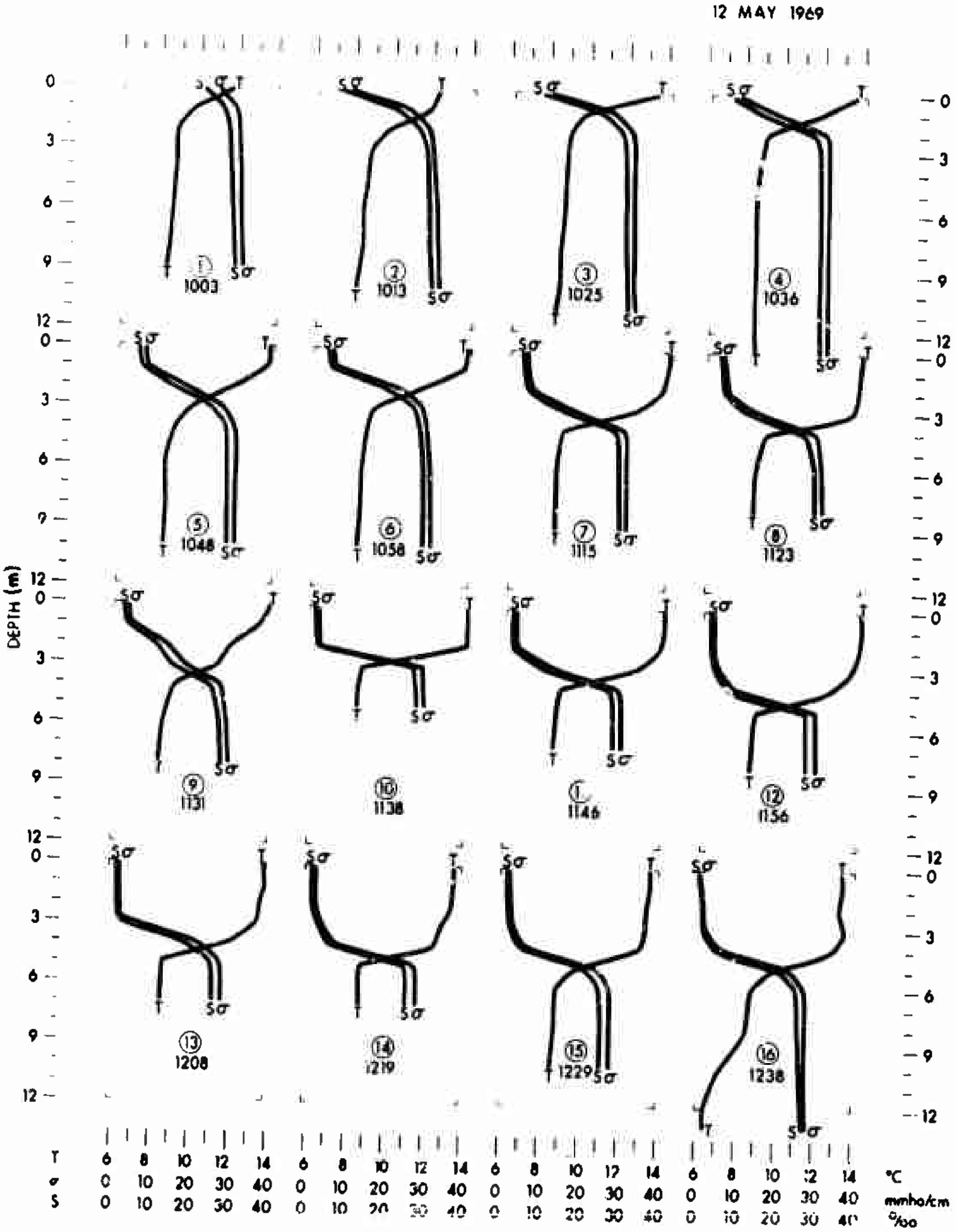


Fig. A-27. Conductivity, Temperature, and Salinity Profiles for 12 May 1969

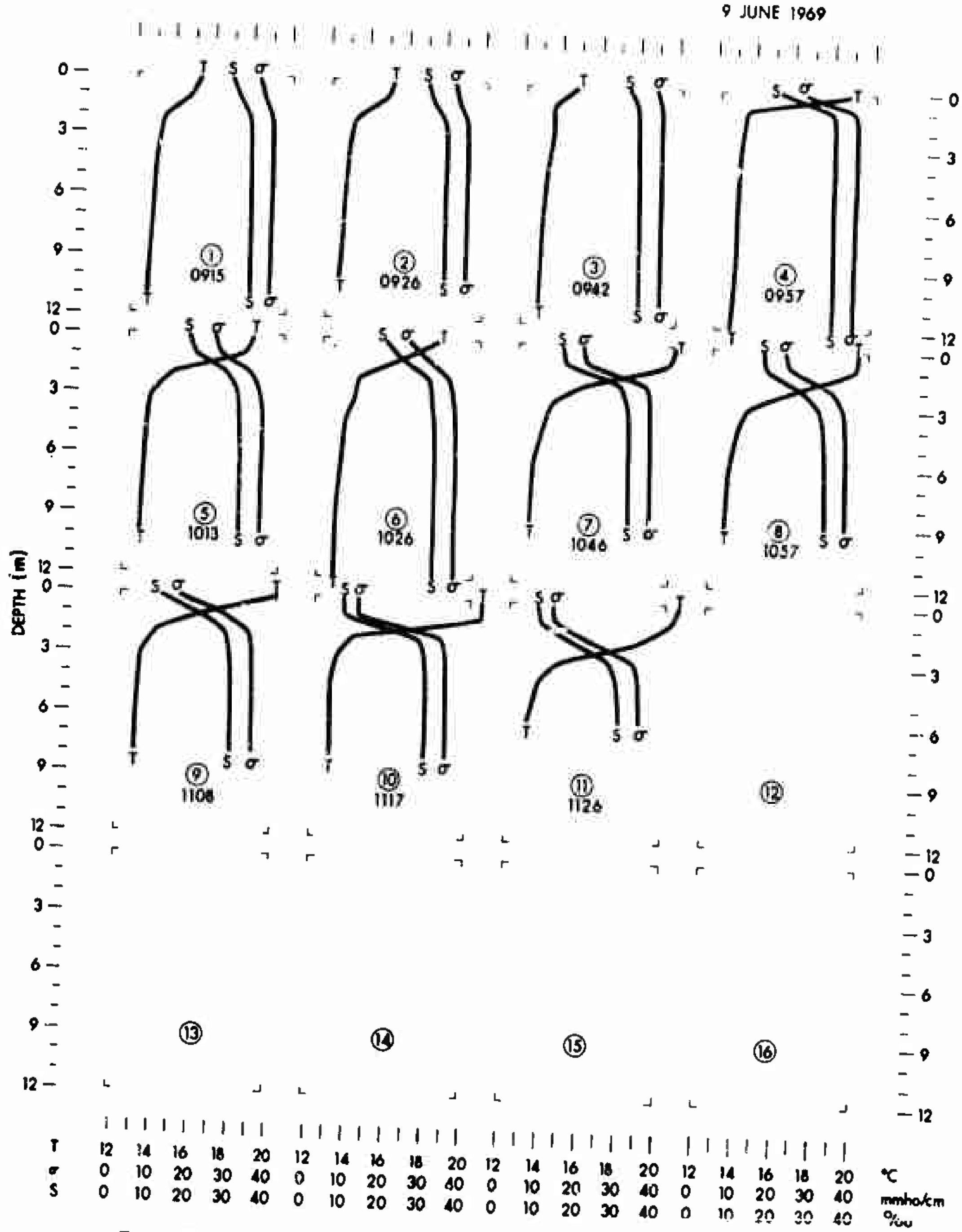


Fig. A-28. Conductivity, Temperature, and Salinity Profiles for 9 June 1969

Appendix B

LOG OF MEASUREMENTS MADE IN THE THAMES RIVER

A log of the measurements made in the Thames River from 5 July 1968 through 9 June 1969 is contained in Table B-1. Also included in the table is a listing of the work done and the reason(s) for discontinuance.

Table B-1

LOG OF MEASUREMENTS MADE IN THE THAMES RIVER FROM 5 JULY 1968 THROUGH 9 JUNE 1969

Date	Data (%)	Weather
5 Jul 1968	100	Clear
12 Jul 1968	100	Clear
19 Jul 1968	66	Overcast Fog and rain
5 Aug 1968	75	Clear
11 Sep 1968	43	Overcast High winds and rough water
16 Sep 1968	100	Clear Wind N 5 knots
26 Sep 1968	31	Partly cloudy Rain and fog in morning Wind NE 10 knots
9 Oct 1968	81	Clear Wind NNE
16 Oct 1968	75	Fog Winds W 15 knots Seas 1-2 ft at Site 1
25 Oct 1968	12	Overcast Fog and rain
1 Nov 1968	68	Clear Winds N 5 -10 knots
18 Nov 1968	50	Clear
9 Jan 1969	37	Clear Wind NNW 8 knots
14 Jan 1969	50	Clear Wind 20 knots Ice above Site 10

Table B-1 (Cont'd)

LOG OF MEASUREMENTS MADE IN THE THAMES RIVER FROM
5 JULY 1968 THROUGH 9 JUNE 1969

Date	Data (%)	Weather
22 Jan 1969	100	Clear Wind NE 10 knots
27 Jan 1969	68	Partly cloudy Wind NW 20 knots Ice above Site 11
5 Feb 1969	31	Partly cloudy Ice above Site 7 Winds WNW 20 knots Seas 2-3 ft at Site 1 Visibility 10 mi
12 Feb 1969	100	Clear Winds calm Seas calm Visibility 10 mi
20 Feb 1969	100	Overcast Winds NNE 20 knots Seas 1-2 ft Visibility 10 mi
6 Mar 1969	100	Clear Winds calm Seas calm Visibility 10 mi
13 Mar 1969	68	Partly cloudy Winds NW 5 knots Visibility 8-10 mi
20 Mar 1969	75	Clear Winds calm Seas calm Visibility 10 mi

Table B-1 (Cont'd)

LOG OF MEASUREMENTS MADE IN THE THAMES RIVER FROM 5 JULY 1968 THROUGH 9 JUNE 1969

Date	Data (%)	Weather
27 Mar 1969	93	Partly cloudy Winds NW 25 knot. Seas NW 2 ft Visibility 10 mi Rough seas at Site 1 prevented measurement
7 Apr 1969	(bo. [illegible]iver and downriver)	Clear Winds W 5 knots Seas calm Visibility 6-7 mi
21 Apr 1969	87	Partly cloudy Winds SE 6 knots Seas calm Visibility 10 mi
28 Apr 1969	12	Clear
30 Apr 1969	50	Partly cloudy Winds NE 10-15 knots Seas NE 0-1 ft Visibility 8 mi Aborted because of threatened rain
5 May 1969	81	Clear Winds calm Seas calm Visibility 10 mi
12 May 1969	100	Clear Winds W 10 knots Seas calm Visibility 14 mi
9 Jun 1969	69	Cloudy Winds 10-15 knots Visibility 5 mi

Appendix C

SUPPORTING DATA FOR SALINITY STRATIFICATION CURVES

The tobles included in this appendix are provided to indicate the data that were used in deriving the graphs of salinity stratification versus location along the river (See Figs. 13 and 14 in the main text). The tables are as follows:

Toble	
C-1	Conversion table for the units used.
C-2	Total daily discharge values for the Quinebaug, Shetucket, and Yontic River gaging stations.
C-3	Various averoges of freshwater discharge values.
C-4	Meosurement dates in order of decreasing values of freshwater discharge.
C-5	Arbitrary division of measurements into two groups for plotting salinity stratification curves.
C-6	Tables of salinity stratification values.

Table C-1

CONVERSION TABLE FOR THE VARIOUS UNITS USED

To convert		To	Multiply by
Volume	m^3/sec	ft^3/sec	35.3144
	ft^3/sec	m^3/sec	0.02832
Velocity	m/sec	knots	1.944
	knots	m/sec	0.5144
Length	m	ft	3.2808
	ft	m	0.3048
	nmi	m	1852.
	m	nmi	5.396×10^{-4}
Area	ft^2	m^2	0.0929
	m^2	ft^2	10.764

Table C-2

TOTAL OF DAILY DISCHARGE VALUES OF QUINEBAUG, SHETUCKET, AND YANTIC RIVERS AS MEASURED AT GAGING STATIONS Q, S, AND Y (ft^3/sec)

Day of Month	1968 Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	1969 Jan	Feb	Mar	Apr	May	Jun
1	5126	2115	3660	3745	422	244	301	354	1065	2790	2016	1060	5409	3678	1482
2	4788	1946	3189	2987	496	241	208	344	1059	2455	1809	1017	4597	3344	1258
3	4301	1799	3532	2379	471	235	138	344	1150	2150	1674	1015	4494	3002	1272
4	3992	1755	3427	2026	436	233	322	333	1572	1797	1678	1053	4206	2705	1127
5	3992	1628	3151	1872	407	289	206	320	4835	1514	1463	1087	4674	2496	986
6	3692	1563	2591	1692	262	372	267	307	4324	1343	1398	1084	2936	2205	891
7	3235	1503	2190	1498	359	380	378	346	3410	1313	1238	1047	7683	2065	924
8	2863	1388	1894	1327	371	385	419	535	2733	1300	1117	1238	6497	2246	822
9	2701	1306	1802	1238	366	444	426	596	2161	1296	1094	1343	5536	2922	739
10	2408	1271	1609	1112	395	404	407	804	1612	1223	1160	1263	5027	4482	670
11	2168	1126	1806	1025	727	449	384	1609	1344	1125	1343	1183	4553	3928	713
12	2008	2786	2591	948	639	485	376	1701	1279	1085	1377	1126	4010	3420	853
13	1940	3231	[illegible]	919	531	630	360	2578	1210	1039	1220	1153	4328	2959	782
14	1859	2691	3137	905	477	668	347	2185	1359	1013	1174	1179	3171	2487	727
15	1824	2221	4469	382	411	789	338	1719	3434	1004	1117	1229	2905	2159	702
16	1844	1957	3818	853	393	752	185	1361	3544	966	1013	1375	2728	2035	936
17	1760	1903	3490	774	402	786	245	1146	2995	929	1012	1521	2871	1902	1070
18	1673	1779	3312	1021	396	695	340	1152	2567	923	1044	1960	2815	1748	901
19	1593	2229	2889	1154	362	508	344	1898	2229	1068	1043	2605	5528	1633	818
20	1506	2509	3190	1058	344	337	371	1930	2061	1229	1023	3174	8219	2767	293
21	1439	2495	3112	867	347	284	376	1647	1887	1229	1022	4483	6344	6419	828
22	1423	2237	2566	785	362	250	353	1438	1742	1137	1047	5926	5734	5072	813
23	1341	2099	2191	723	367	228	176	1218	2025	1121	1006	5148	10830	3750	727
24	1409	2270	1908	642	332	221	197	1055	2479	1442	1113	5114	9948	2994	754
25	4394	2331	1907	642	335	213	264	946	1939	2525	1194	11440	9240	2639	749
26	4656	1949	3661	596	317	298	348	876	1758	2496	1241	16900*	7961	2479	716
27	3727	1701	3903	549	294	345	391	864	1713	2039	1107	12227	6235	2233	666
28	3164	1543	4467	488	283	258	401	833	1820	1676	1130	9829	5074	1999	612
29	2690	1984	5549	445	271	125*	397	1035	3661	1395		8437	4516	1728	554
30	2342	4912	4592	437	265	246	382	1191	3223	1367		7224	3959	1832	497
31		4392		404	254		373		2688	1863		6373		1755	
Column Total	81852	66119	96883	36008	12194	11784	10020	32655	70878	45852	34873	120813	167028	87083	25382
Monthly Mean	2728.4	2132.9	3229.4	1161.5	393.4	392.8	323.2	1086.5	2286.4	1479.1	1245.4	3897.2	5567.6	2809.1	846.1

*Min. 125

*Max. 16900

Table C-3

VARIOUS AVERAGES OF FRESHWATER DISCHARGE FROM 5 JULY 1968 THROUGH 9 JUNE 1969 (ft^3/sec)

Month and Day	Discharge on Day 1*	Average Discharge for Days 1, 2**	Discharge on Day 2	Average Discharge for Days 2, 3†	Discharge on Day 3	Average Discharge for Days 1, 2, 3	Average Discharge for Days 2, 3, 4‡
Jul 5	1872	1949	2026	2212	2397	2098	2470
12	948	987	1025	1069	1112	1028	1125
19	1154	1088	1021	896	771	982	882
Aug 5	407	411	436	454	471	438	468
Sep 16	752	770	789	728	668	736	696
26	298	256	213	217	221	244	221
Oct 9	426	423	419	398	378	408	355
16	185	262	338	343	347	290	349
Nov 1	354	364	373	378	382	369	384
Jan 9	1296	1298	1300	1307	1313	1303	1319
14	1013	1026	1039	1062	1085	1046	1083
22	1137	1233	1229	1229	1229	1232	1175
27	2039	2268	2496	2511	2525	2687	2154
Feb 5	1463	1570	1678	1676	1674	1605	1720
12	1377	1360	1343	1252	1160	1293	1199
20	1023	1033	1043	1044	1044	1037	1033
Mar 6	1084	1086	1087	1070	1053	1075	1052
13	1153	1140	1126	1159	1183	1154	1191
20	3174	2889	2605	2282	1960	2579	2029
27	12227	14564	16900	14170	11440	13522	11151
Apr 7	7683	7809	7936	6305	4674	6764	5605
21	6344	7282	8219	6874	5528	6697	5521
30	3959	4238	4516	4795	5074	4516	5275
May 5	2496	2600	2705	2854	3002	2734	3017
12	3420	3674	3928	4205	4482	3943	3777
Jun 9	739	780	822	873	924	828	879

*Day 1 is the date of measurement.
**Day 2 is the day before the date of measurement.
†Day 3 is two days before the date of measurement.
‡Day 4 is three days before the date of measurement.

Table C-4

MEASUREMENT DATES IN ORDER OF DECREASING VALUES OF FRESHWATER DISCHARGE FROM 5 JULY 1968 THROUGH 9 JUNE 1969

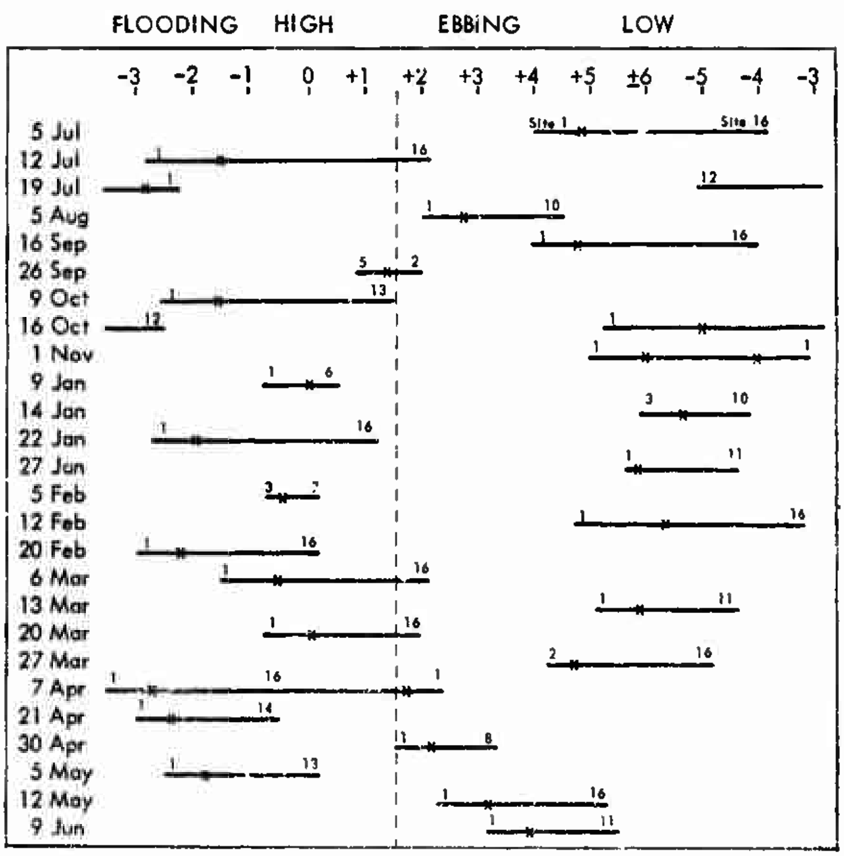
Discharge on Day 1*	Average Discharge Days 1, 2**	Discharge on Day 2	Average Discharge Days 2, 3†	Discharge on Day 3	Average Discharge Days 1, 2, 3	Average Discharge Days 2, 3, 4‡
Mar 27	Mar 27	Mar 27	Mar 27	Mar 27	Mar 27	Mar 27
Apr 7	Apr 7	Apr 21	Apr 21	Apr 21	Apr 7	Apr 7
Apr 21	Apr 21	Apr 7	Apr 7	Apr 30	Apr 21	Apr 21
Apr 30	Apr 30	Apr 30	Apr 30	Apr 7	Apr 30	Apr 30
May 12	May 12	May 12	May 12	May 12	May 12	May 12
Mar 20	Mar 20	May 5	May 5	May 5	May 5	May 5
May 5	May 5	Mar 20	Jan 27	Jan 27	Jan 27	Jul 5
Jan 27	Jan 27	Jan 27	Mar 20	Jul 5	Mar 20	Jan 27
Jul 5	Jul 5	Jul 5	Jul 5	Mar 20	Jul 5	Mar 20
Feb 5	Feb 5	Feb 5	Feb 5	Feb 5	Feb 5	Feb 5
Feb 12	Feb 12	Feb 12	Jan 9	Jan 9	Jan 9	Jan 9
Jan 9	Jan 9	Jan 9	Feb 12	Jan 22	Feb 12	Feb 12
Jul 19	Jan 22	Jan 22	Jan 22	Mar 13	Jan 22	Mar 13
Mar 13	Mar 13	Mar 13	Mar 13	Feb 12	Mar 13	Jan 22
Jan 22	Jul 19	Mar 6	Mar 6	Jul 12	Mar 6	Jul 12
Mar 6	Mar 6	Feb 20	Jul 12	Jan 14	Jan 14	Jan 14
Feb 20	Feb 20	Jan 14	Jan 14	Mar 6	Feb 20	Mar 6
Jan 14	Jan 14	Jul 12	Feb 20	Feb 20	Jul 12	Feb 20
Jul 12	Jul 12	Jul 19	Jul 19	Jun 9	Jul 19	Jul 19
Sep 16	Jun 9	June 9	Jun 9	Jul 19	Jun 9	Jun 9
Jun 9	Sep 16	Sep 16	Sep 16	Sep 16	Sep 16	Sep 16
Oct 9	Oct 9	Aug 5	Aug 5	Aug 5	Aug 5	Aug 5
Aug 5	Aug 5	Oct 9	Oct 9	Nov 1	Oct 9	Nov 1
Nov 1	Nov 1	Nov 1	Nov 1	Oct 9	Nov 1	Oct 9
Sep 26	Oct 16	Oct 16	Oct 16	Oct 16	Oct 16	Oct 16
Oct 16	Sep 26	Sep 26	Sep 26	Sep 26	Sep 26	Sep 26

*Day 1 is the date of measurement.
**Day 2 is the day before the date of measurement.
†Day 3 is two days before the date of measurement.
‡Day 4 is three days before the date of measurement.

Table C-5

TIDAL CONDITIONS DURING THE PERIODS
OF MEASUREMENT

FLOODING & HIGH TIDE		EBBING & LOW TIDE	
Apr 21*	High-2.3 hr	Mar 27	Low-1.2 hr
Apr 7	High-2.8	Apr 30	Low-4.0
May 5	High-1.8	May 12	Low-2.8
Mar 20	High	Jan 27	Low+0.3
Feb 5	High-0.4	Jul 5	Low-1.3
Jan 9	High	Feb 12	Low-0.3
Jan 22	High-1.9	Mar 13	Low+0.1
Mar 6	High-0.6	Jan 14	Low-0.8
Jul 12	High-1.5	Jun 9	Low-2.1
Feb 20	High-2.2	Sep 16	Low-1.2
Jul 19	High-2.8	Aug 5	Low-3.2
Oct 9	High-1.6	Nov 1	Low
Sep 26	High+1.5	Oct 16	Low+1.0



*(The dates are arranged in order of decreasing values of freshwater discharge given in Table C-4 for the average of days 2 and 3).
(x marks the time of each Site 4 measurement).

Table C-6

SALINITY STRATIFICATION* FOR FLOODING AND HIGH TIDE AND EBBING AND LOW TIDE
FROM 5 JULY 1968 THROUGH 9 JUNE 1969

a. Flooding and High Tide

Site No.	21 Apr	7 Apr (Upriver)	5 May	20 Mar	5 Feb	22 Jan	6 Mar	12 Jul	20 Feb	19 Jul	9 Oct
1	0.691	0.586	0.233	0.283		0.046	0.019	0.036	0.005	0.024	
2	0.758	0.663	0.338	0.391		0.103	0.128	0.165	0.057		0.055
3	0.807	0.736	0.431	0.413	0.234	0.143	0.174	0.233	0.090	0.138	0.070
4	0.894	0.855	0.626	0.526	0.439	0.229	0.252	0.235	0.135	0.199	0.072
5	1.02	0.967	0.721	0.574	0.569	0.301	0.290	0.423	0.191	0.204	0.136
6	1.02	0.954	0.643		0.329	0.260	0.274	0.449	0.175	0.398	0.128
7	1.25	1.17	0.792	0.771	0.683	0.368	0.335	0.426	0.231	0.496	0.123
8	1.29	1.25	0.851	0.788		0.368	0.421		0.220	0.627	0.095
9	1.36	1.31	0.809	0.872		0.526	0.392	0.533	0.285	0.722	0.276
10	1.43	1.43	0.895	0.988		0.595	0.538	0.564	0.320	0.749	0.269
11	1.66	1.84	0.991			0.684	0.600	0.636	0.326	1.00	0.369
12	1.82	1.95	1.13	1.10		0.785	0.848	0.840	0.442	1.38	0.408
13	1.96	2.12	1.22			0.924	0.895	0.970	0.507		0.355
14	2.66	3.17		1.52		1.03	1.09	1.20	0.743		
15		3.27				1.06	1.17	1.19	0.880		
16				1.52		1.04	1.13	1.18	0.683		

b. Ebbing and Low Tide

Site No.	27 Mar	7 Apr (Downriver)	30 Apr	12 May	27 Jan	5 Jul	12 Feb	13 Mar	14 Jan	9 Jun	16 Sep	5 Aug	16 Oct
1		0.531	0.312	0.291	0.100	0.062	0.165	0.092		0.182	0.034	0.016	0.022
2		0.648	0.406	0.809	0.182	0.068	0.166	0.134		0.178	0.102	0.076	0.088
3	0.948	0.601	0.603	0.839	0.302	0.076	0.029	0.167	0.198	0.104	0.121		0.118
4	1.07		0.825	0.901	0.539	0.084	0.224	0.277	0.236	0.506	0.226	0.188	0.171
5	1.40	1.02	0.913	1.01	0.643	0.750	0.280	0.335		0.511	0.270	0.225	0.179
6	1.51	1.02	0.960	1.08	0.678	1.01	0.464	0.407	0.460	0.502	0.344		0.205
7	1.67	1.27	1.05	1.30	0.846	1.09	0.662	0.430	0.780	0.709	0.462	0.292	0.234
8	2.03	1.30	1.06	1.34	0.875	1.11	0.718	0.496	0.861	0.649	0.475	0.419	0.253
9		1.32		1.31	0.932	1.13	0.680	0.561	0.912	0.733	0.633	0.551	0.314
10	2.62	1.38		1.36	0.974	1.21	0.801	0.623	0.997	0.884	0.732	0.611	0.349
11		1.66		1.2[illegible]	0.978	1.22	0.794	0.597		0.928	0.703		0.354
12		1.73		1.83		1.28	1.00				0.729		0.628
13		2.02		1.7[illegible]		1.46	1.13				0.897		
14		3.27		1.84		1.48	1.22				1.02		
15		3.21		1.64		1.56	1.38				1.03		
16				1.62		1.49	1.51				1.11		

$$^{*}\frac{\delta S}{S_x} = \frac{\text{top-to-bottom salinity difference}}{\text{mean salinity through river cross section}}$$

Appendix D

GRAPHS OF SOUND VELOCITY VERSUS DEPTH

A program prepared by the Data Analysis and Computing Center at NUSC was used to calculate the sound velocity as a function of temperature, salinity, depth, and latitude. The program is based on Wilson's equations,[D1] which were developed by least-squares fit to 581 measured points in the temperature range $-4^\circ C < T < 30^\circ C$, the pressure range $1.033\ kg/cm^2 < P < 1000\ kg/cm^2$, and the salinity range $0‰ < S < 37‰$.

The equation for the speed of sound in sea water is given by

$$
\begin{aligned}
V &= 1449.14 + V_T + V_P + V_S + V_{STP} \\
V_T &= 4.5721T - 4.4532 \times 10^{-2} T^2 - 2.6045 \times 10^{-4} T^3 + 7.9851 \times 10^{-6} T^4 \\
V_P &= 1.60272 \times 10^{-1} P + 1.0268 \times 10^{-5} P^2 + 3.5216 \times 10^{-9} P^3 - 3.3603 \times 10^{-12} P^4 \\
V_S &= 1.39799(S-35) + 1.69202 \times 10^{-3}(S-35)^2 \\
V_{STP} &= (S-35)(-1.1244 \times 10^{-2} T + 7.7711 \times 10^{-7} T^2 + 7.7016 \times 10^{-5} P - 1.2943 \times 10^{-7} P^2 \\
&\quad + 3.1580 \times 10^{-8} PT + 1.5790 \times 10^{-9} PT^2) + P(-1.8607 \times 10^{-4} T + 7.4812 \times 10^{-6} T^2 \\
&\quad + 4.5283 \times 10^{-8} T^3) + P^2(-2.5294 \times 10^{-7} T + 1.8563 \times 10^{-9} T^2) + P^3(-1.9646 \times 10^{-10} T),
\end{aligned}
$$

where

V_T, V_P, V_S, V_{STP} are changes introduced by temperature, pressure, salinity, and simultaneous changes due to all three parameters.

The measured data easily fit the range of the equation. However, the sound-velocity profiles represent the velocity structure only at the time of measurement of the physical parameters. A velocity contour can not be established nor can anything be said about future predictions.

[D1] W. D. Wilson, "Equation for the Speed of Sound in Sea Water," *Journal of the Acoustical Society of America*, vol. 32, no. 10, October 1960, p. 1357.

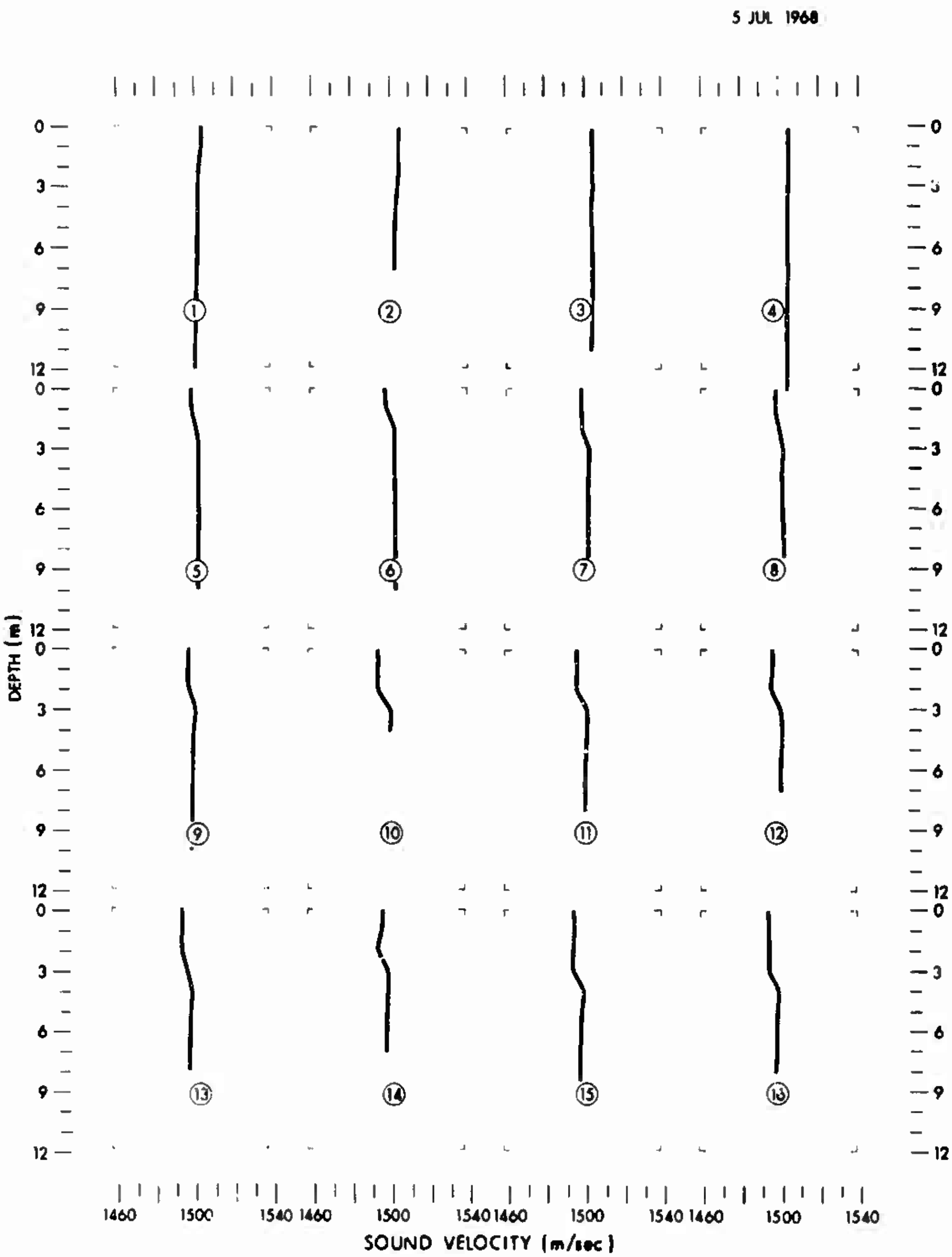


Fig. D-1. Sound Velocity Profiles for 5 July 1968

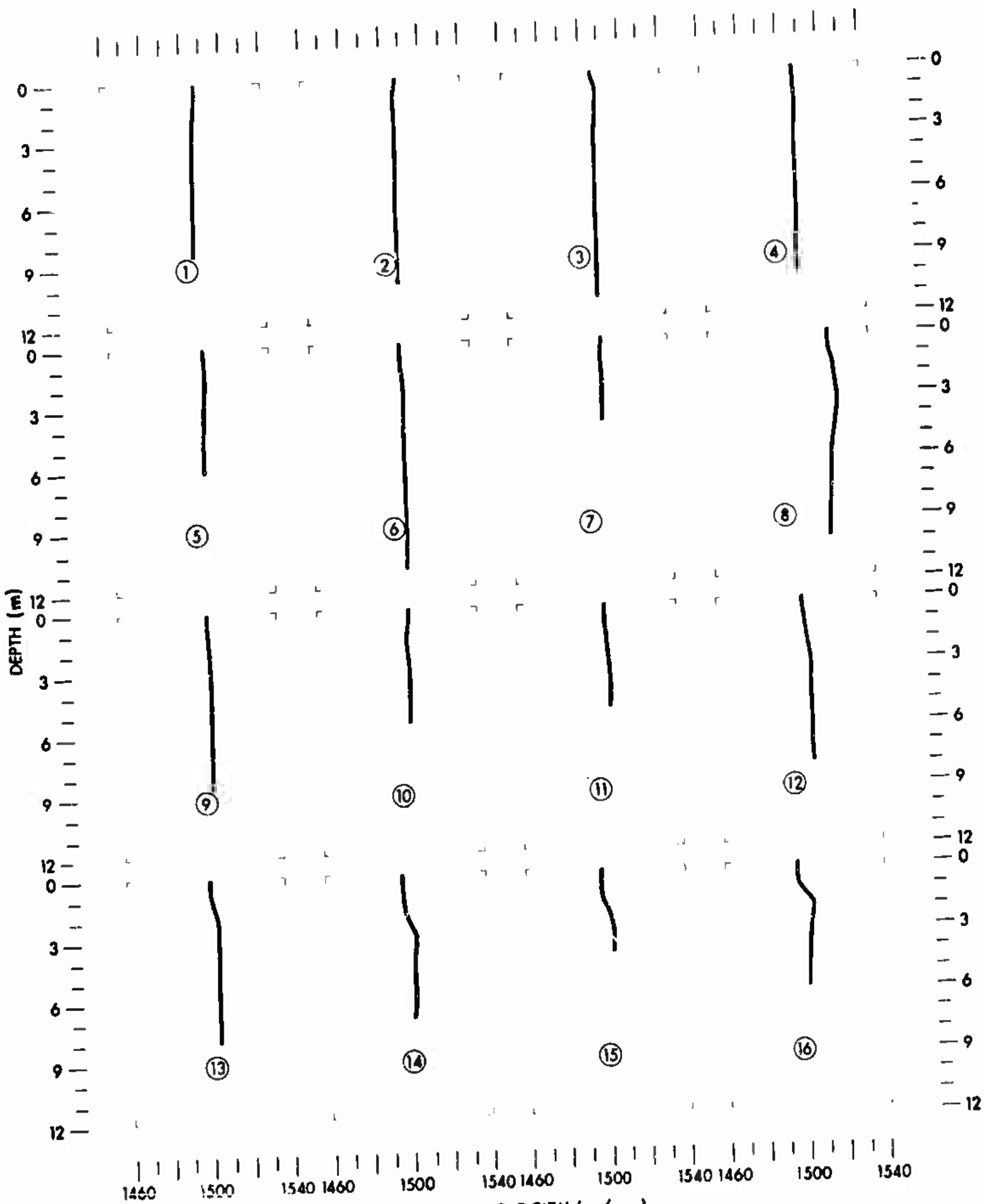


Fig. D-2. Sound Velocity Profiles for 12 July 1968

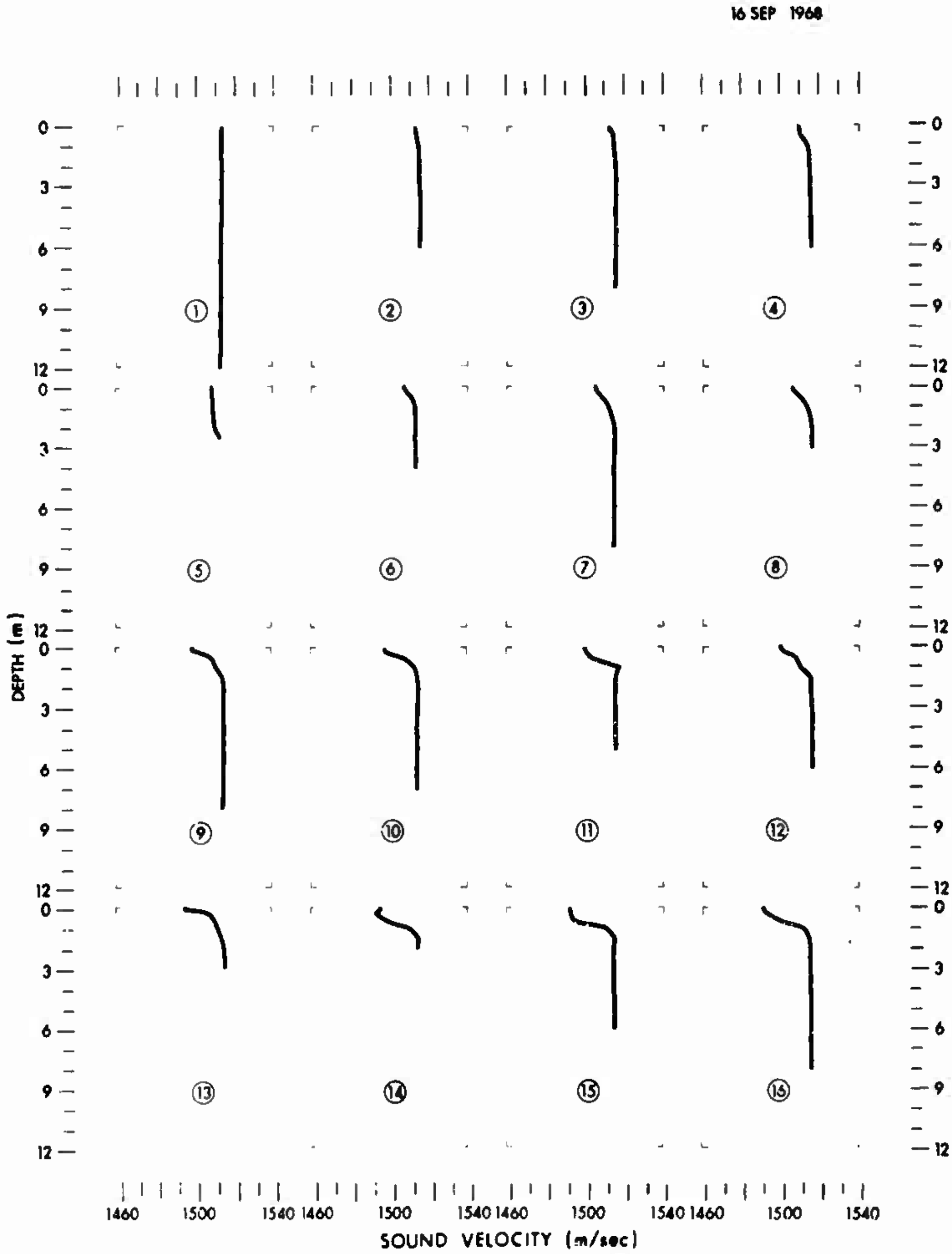


Fig. D-3. Sound Velocity Profiles for 16 September 1968

16 OCT 1968

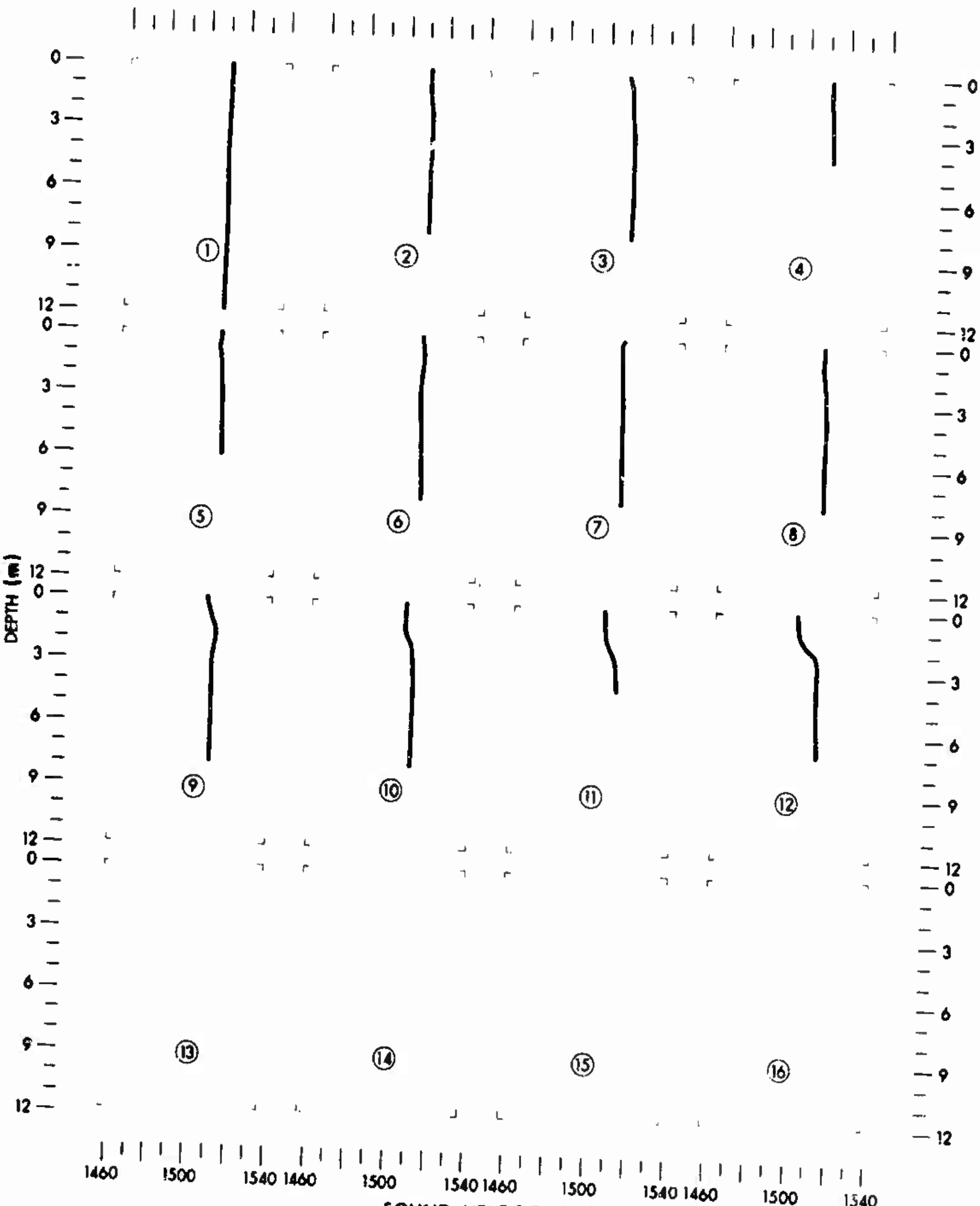


Fig. D-4. Sound Velocity Profiles for 16 October 1968

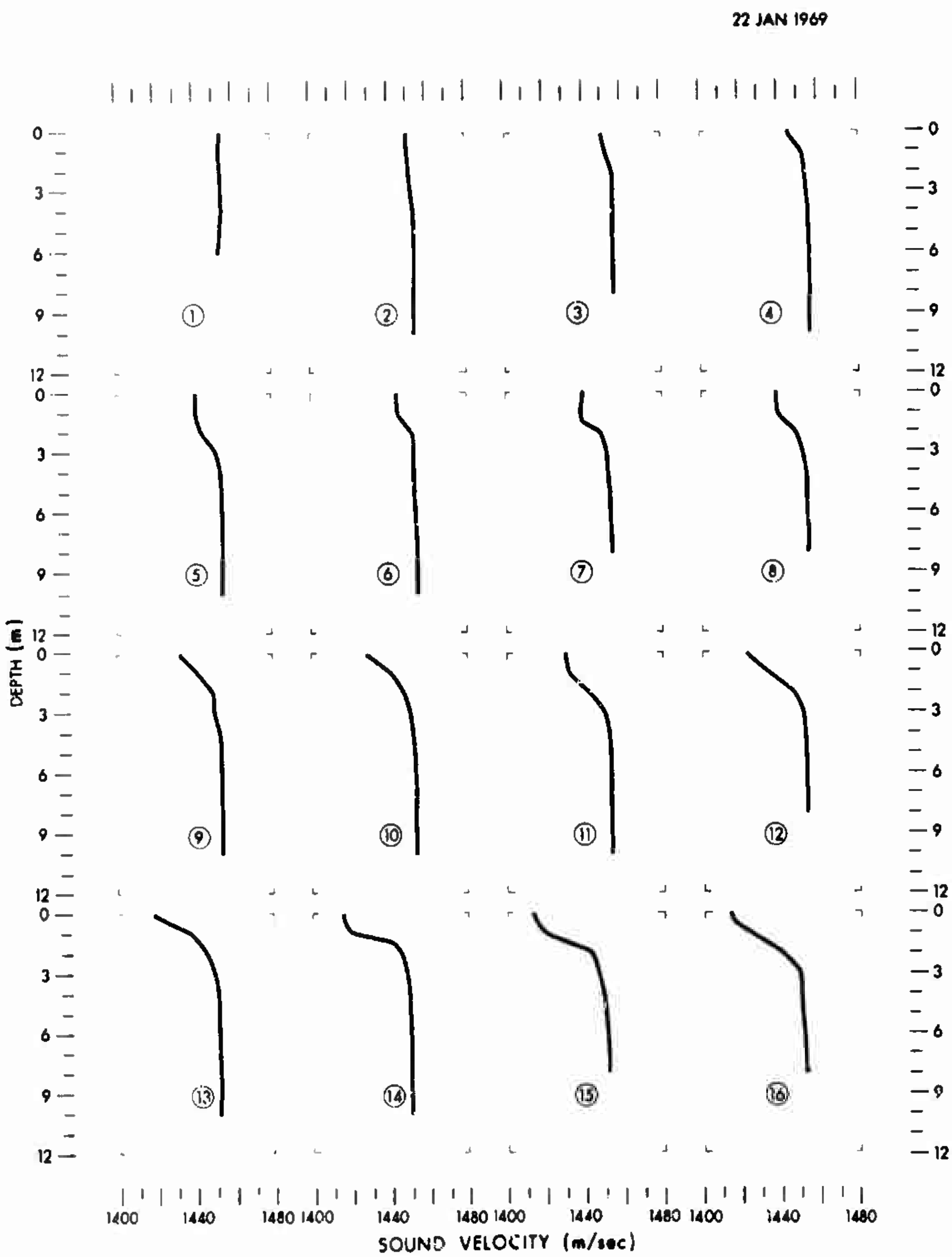


Fig. D-5. Sound Velocity Profiles for 22 January 1969

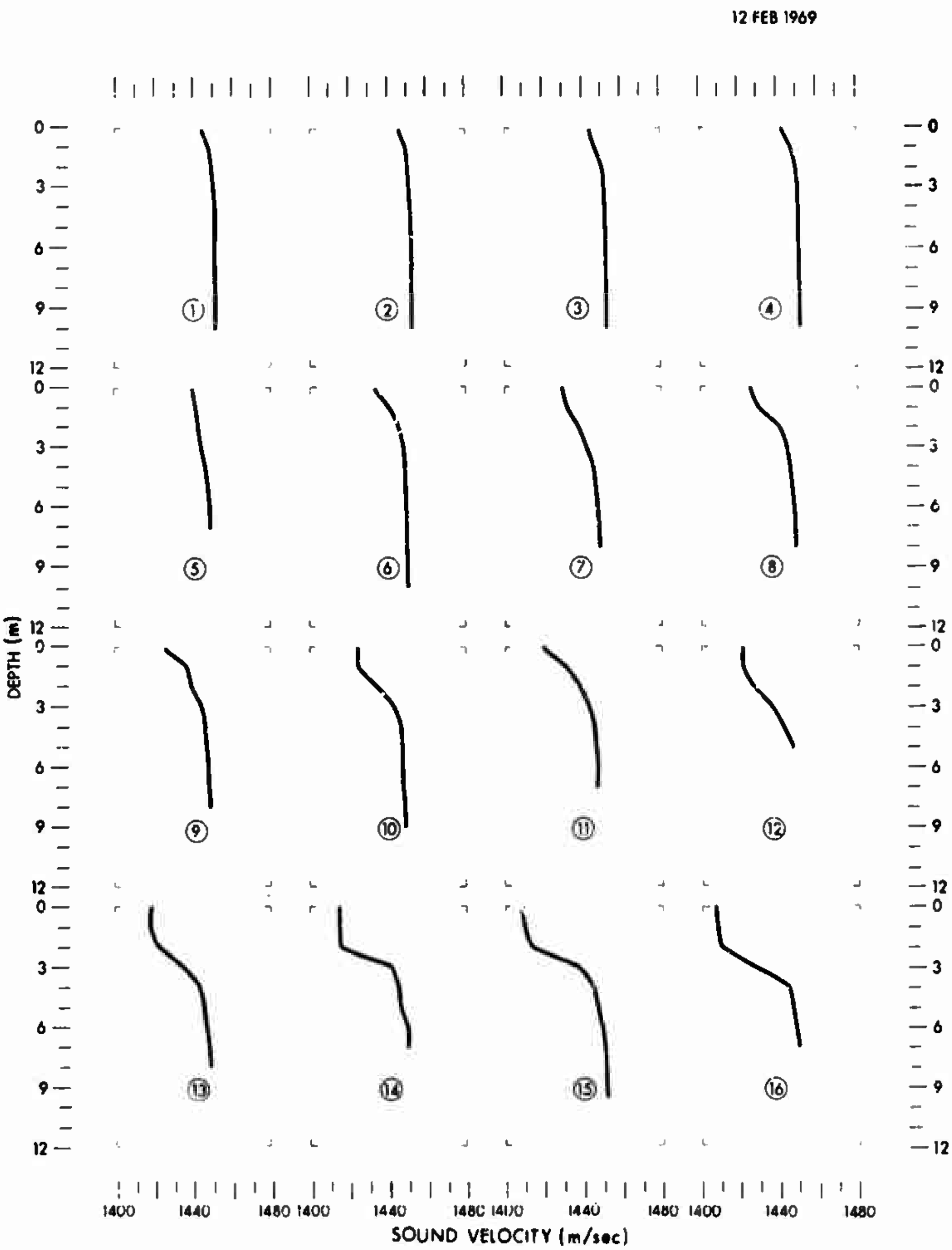


Fig. D-6. Sound Velocity Profiles for 12 February 1969

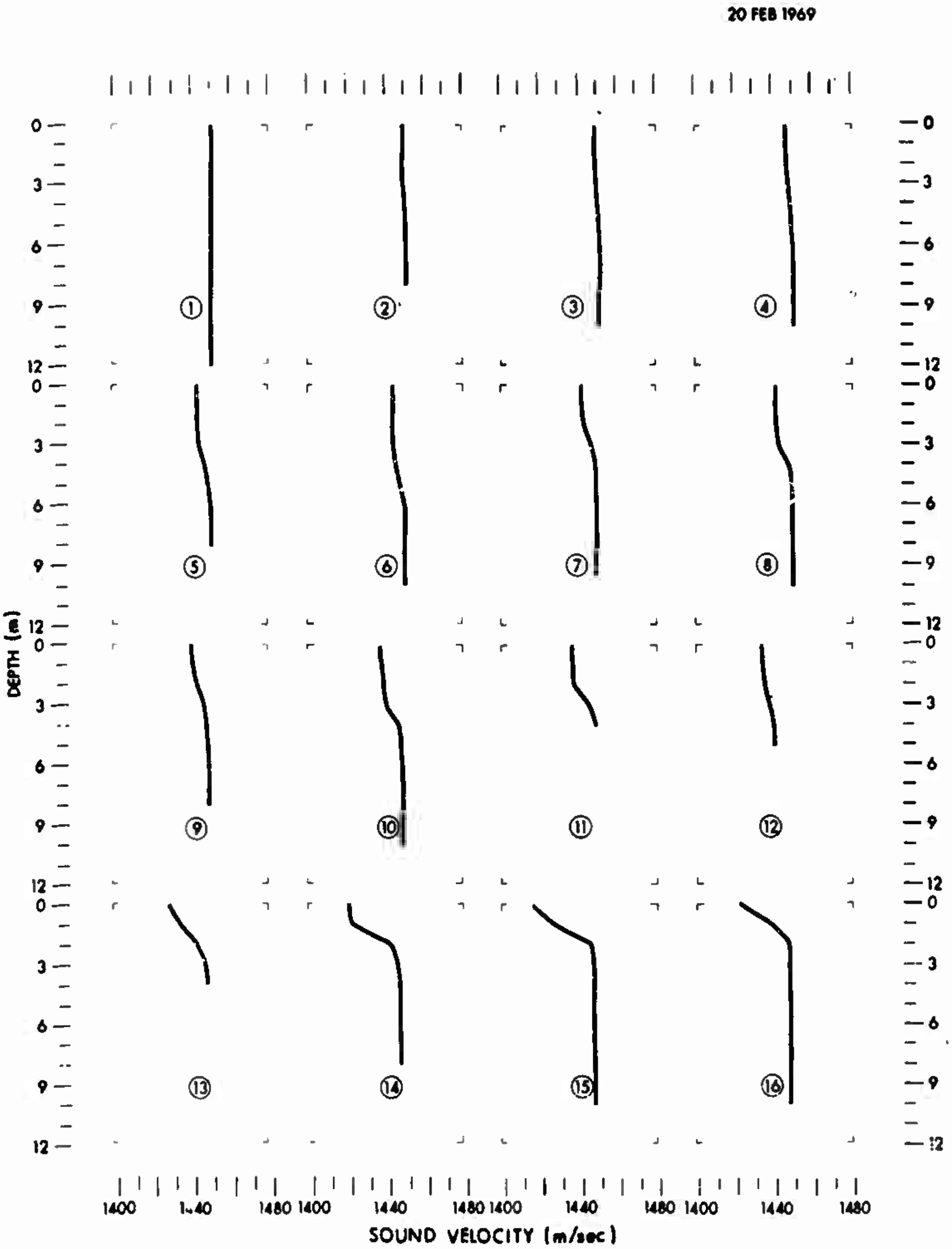


Fig. D-7. Sound Velocity Profiles for 20 February 1969

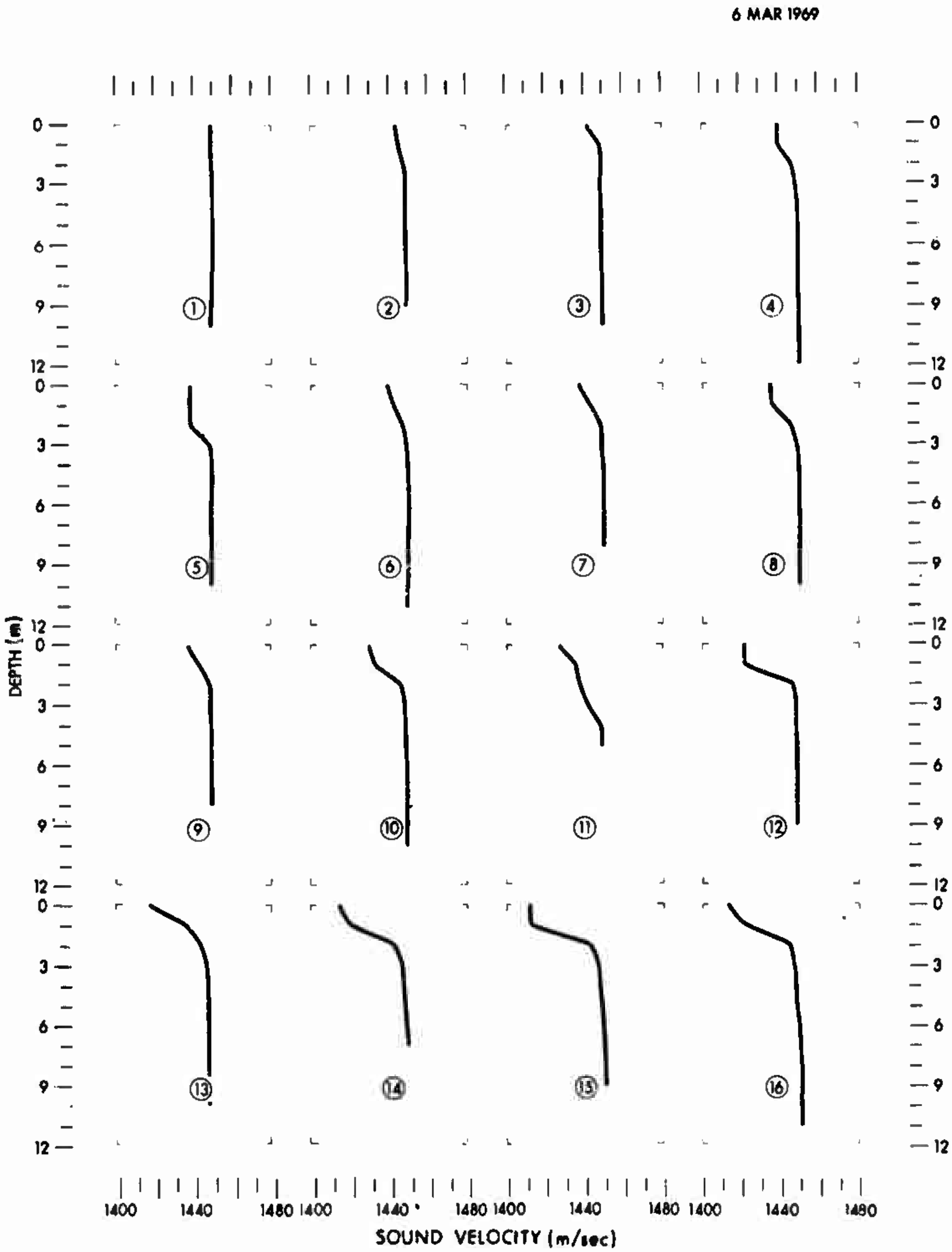


Fig. D-8. Sound Velocity Profiles for 6 March 1969

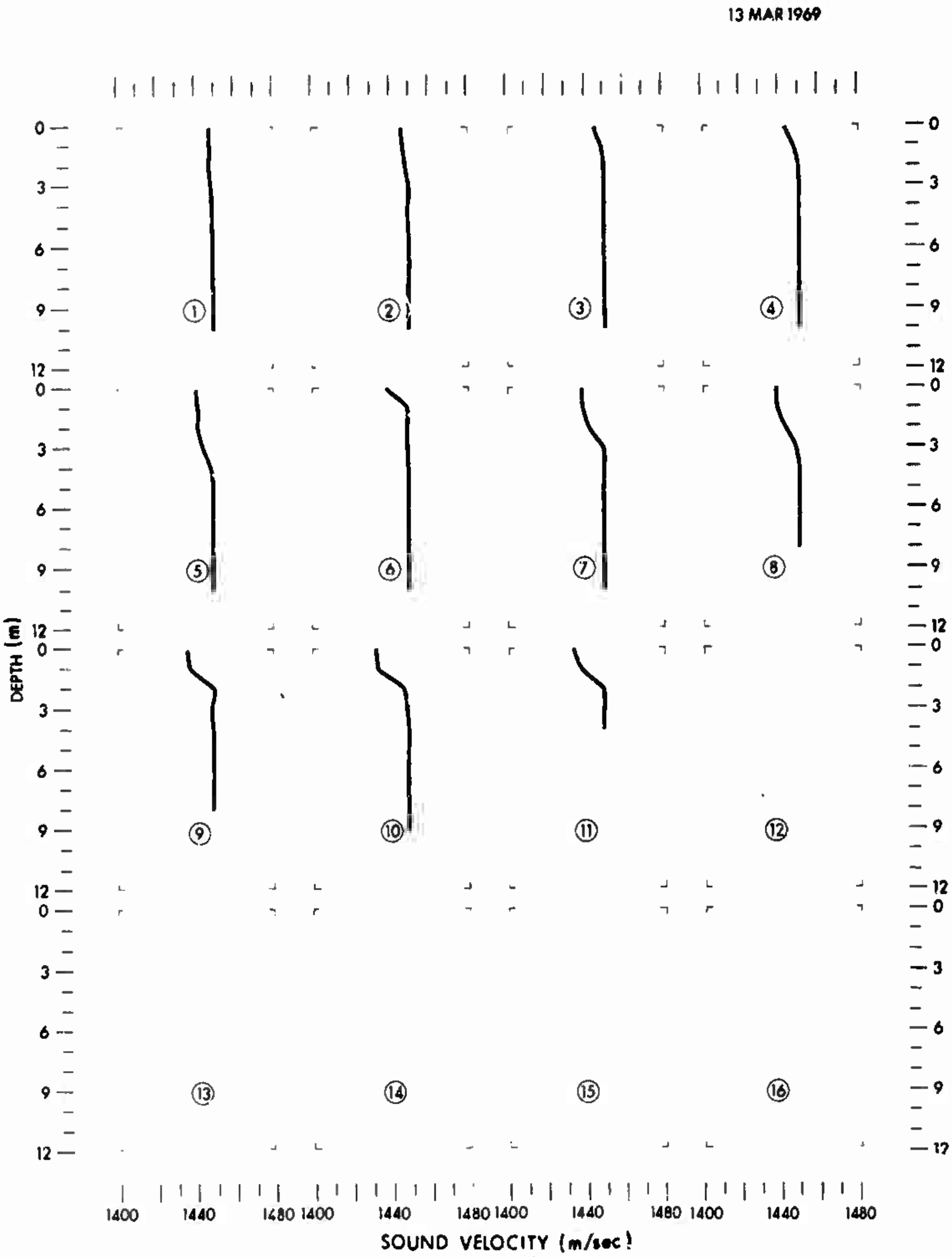


Fig. D-9. Sound Velocity Profiles for 13 March 1969

20 MAR 1969

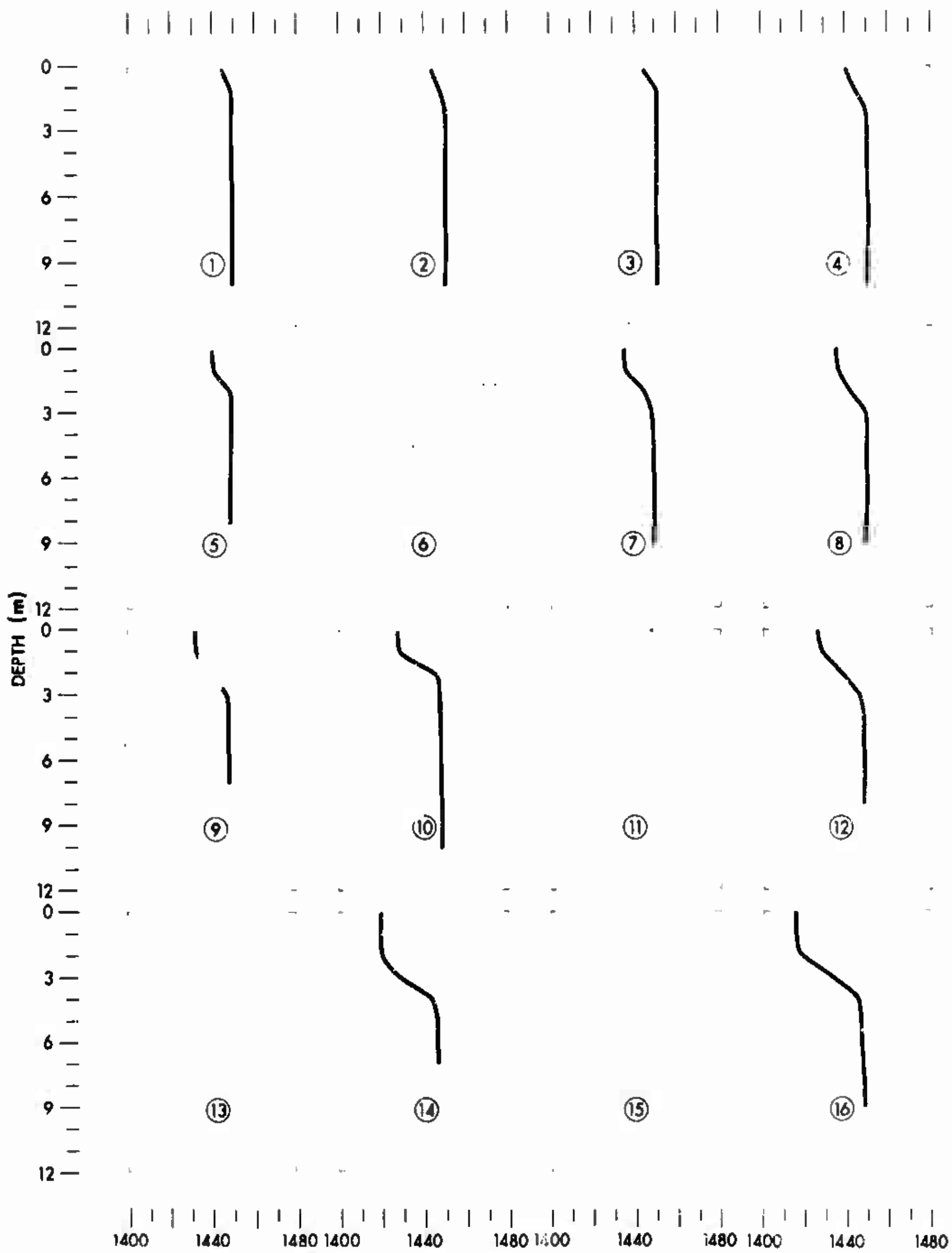


Fig. D-10. Sound Velocity Profiles for 20 March 1969

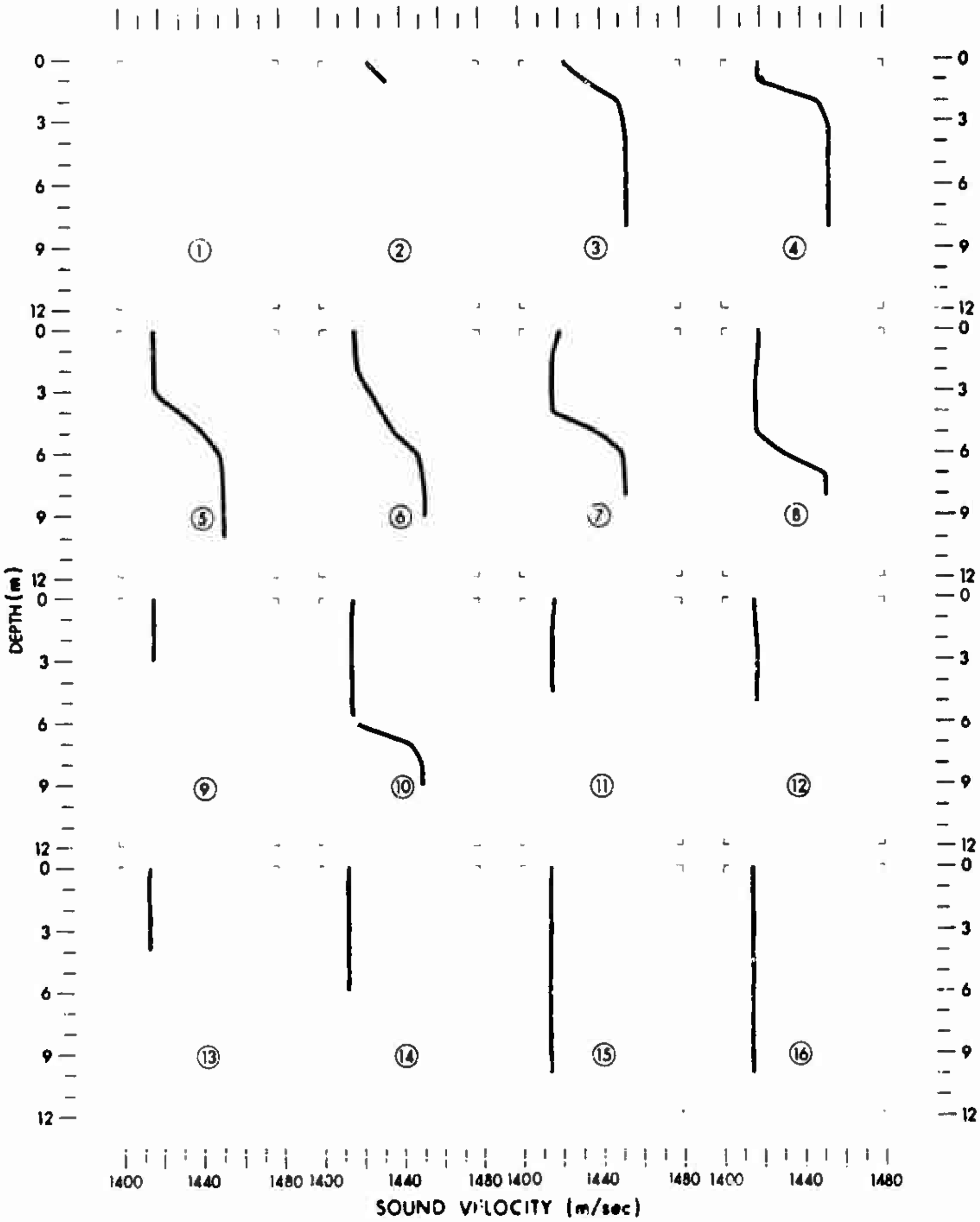


Fig. D-11. Sound Velocity Profiles for 27 March 1969

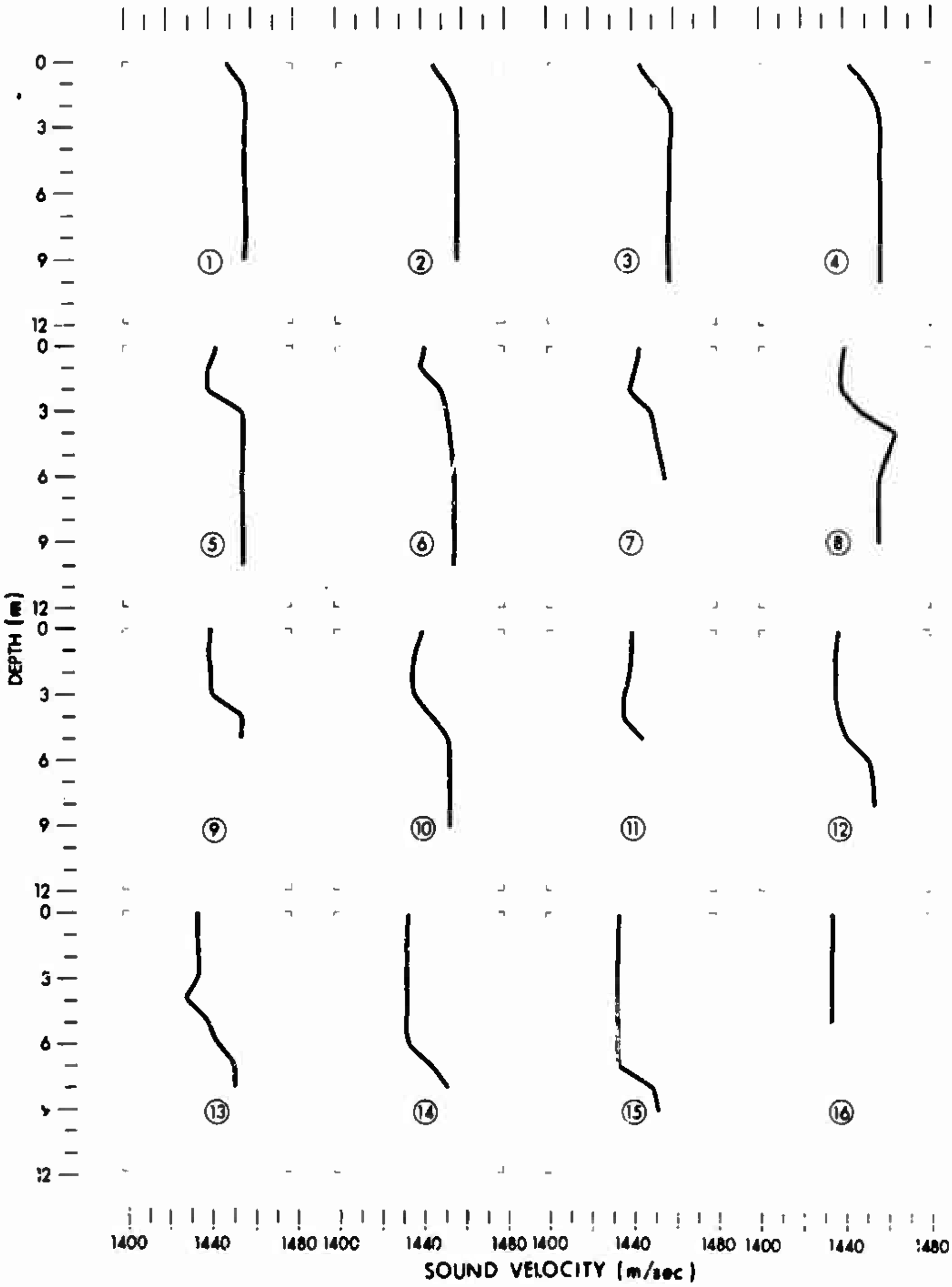


Fig. D-12. Sound Velocity Profiles for 7 April 1969, Upriver

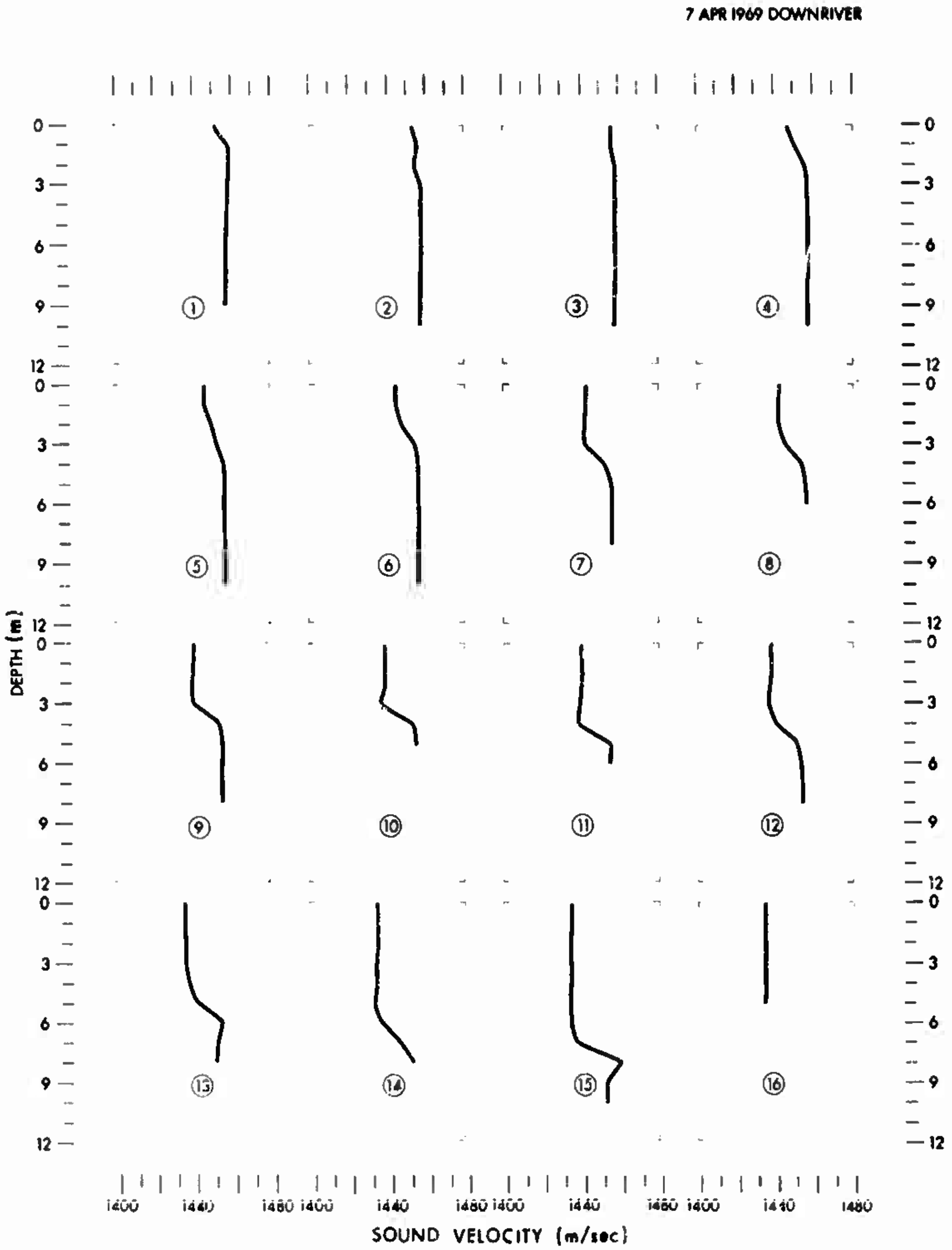


Fig. D-13. Sound Velocity Profiles for 7 April 1969, Downriver

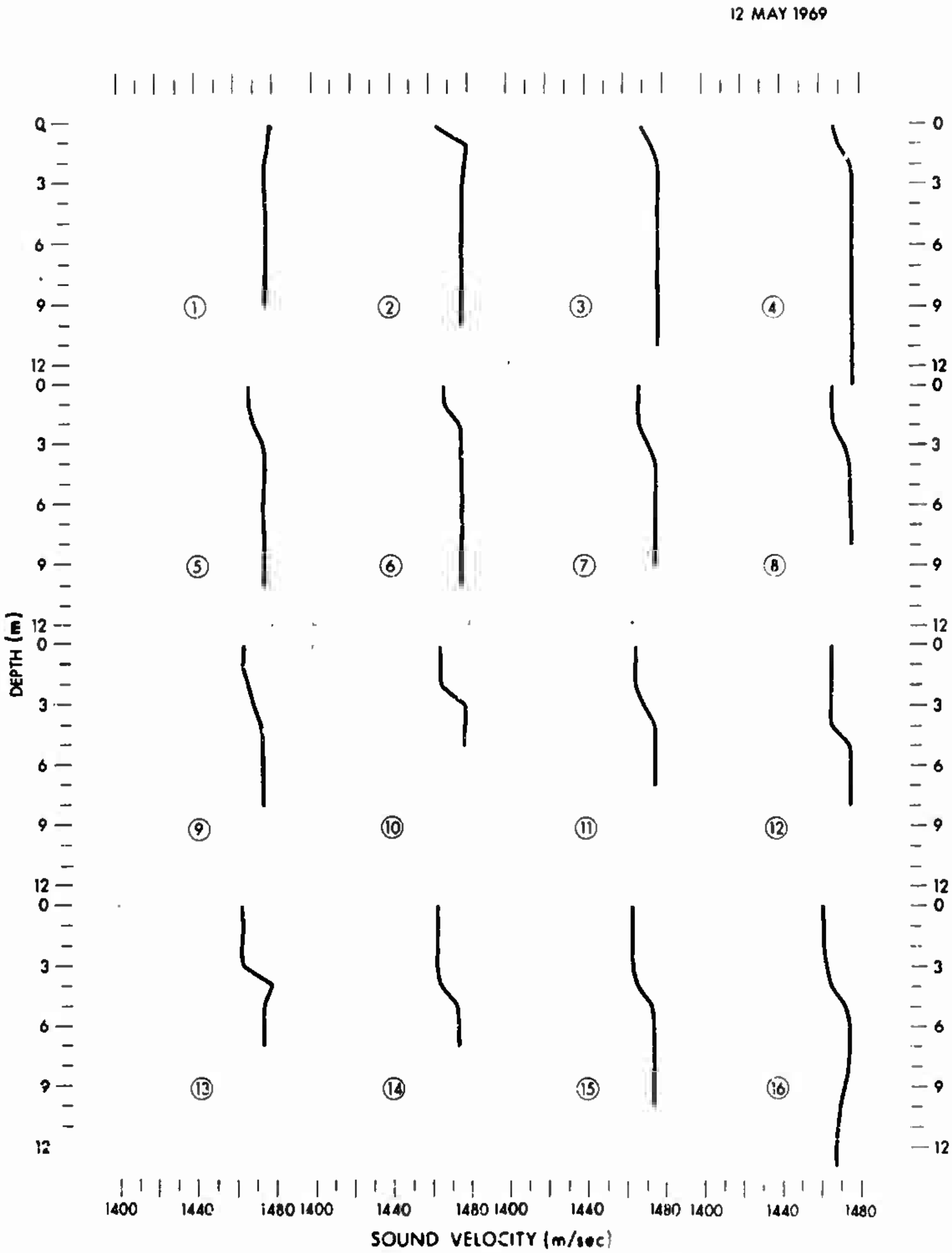


Fig. D-14. Sound Velocity Profiles for 12 May 1969